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BOEING COMMERCIAL AIRPLANE COMPANY

FINAL DESIGN PROPOSAL

ZETA GROUP - VALKYRIE

A Proposal in Response to a Commercial Air Transportation Study

May 1991

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Notre Dame, IN 46556

1. *Executive Summary*

The *Valkyrie*

The *Valkyrie* flying wing concept is a remotely piloted technology demonstrator designed to serve as a high volume commuter transport in Aeroworld. The technology demonstrator seeks to validate the flying wing design as a superior alternative to the conventionally configured aircraft used in the modern airline industry.

The 5.02 lb *Valkyrie* has a planform area of 1440 in^2 (10 ft^2) and a wingspan of 84 in (7 ft), which results in an aspect ratio of 4.9. The root and tip chords measure 23 and 11 in, respectively, forming a taper ratio of 0.48.

The *Valkyrie* employs the NACA 2R$_2$12 airfoil section. A 2° reflex in the trailing edge of this airfoil provides a zero moment coefficient about the aerodynamic center over the applicable range of angles of attack. Furthermore, the rear twenty percent of the chord across the entire span comprises the elevator and ailerons. This configuration, along with a judicious positioning of the center of gravity location, allows the *Valkyrie* to trim during cruise at an angle of attack of 8° with a corresponding elevator deflection of -8°. Although reflexing the trailing flap to trim does increase the drag generate by the wing by raising the C_{D_0} to 0.0314, the overall drag produced by this configuration remains small compared to similarly sized conventional designs with drag–inducing fuselages. Additionally, the 2R$_2$12 airfoil allows the aircraft to generate a maximum C_L of approximately 0.89 at an angle of 14°. However, the maximum C_L for a trimmed configuration is 0.75 at an angle of attack of 14° and a elevator deflection of -14°.

A leading edge wing sweep of 13.2° and a 2° dihedral have been incorporated to provide lateral stability. Ailerons have been designed to provide enough roll control power to navigate a 60 foot radius turn. Yaw stability is provided by triple vertical stabilizers. Yaw control is achieved through the use of a rudder on the center vertical stabilizer. With this configuration, it is possible to land in a crosswind of 10 ft/s.

The *Valkyrie* is semi-monocoque structure manufactured from spruce and balsa wood covered in plastic mylar skin. The internal ribs are spaced 3.5 in. apart so to provide comfortable seating for the maximum carrying capacity of 100 passengers. The NACA 2R$_2$12 airfoil, with its 12% maximum thickness (t/c) provides sufficient volume to comfortably carry the maximum passenger load. In addition to adequate passenger space, the *Valkyrie* must have sufficient usable volume to house the fuel and control system. Two large, solid balsa wood ribs form the central corridor of the aircraft, housing the motor, batteries and avionics.

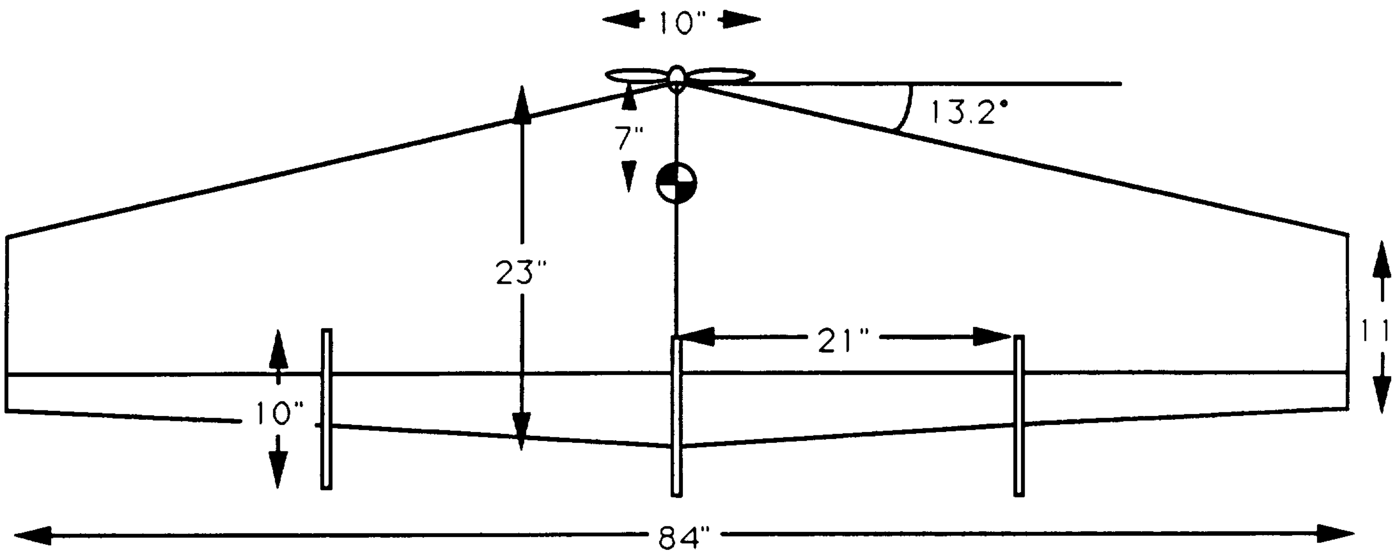
The AstroFlight Cobolt 25 electric engine will power the *Valkyrie* with a Tornado 10-6 propeller. This engine/propeller combination draws the lowest current, 6.3 amps, and requires the fewest number of batteries, 8, to power an aircraft of this size and configuration. This engine/propeller combination also provides a static thrust of 3.9 lbs, yielding a take off distance of 16.3 ft. The current draw at take off is 15.1 amps. The structure housing the engine and avionics is constructed of balsa wood, as is the wing itself. Additional materials used in the construction of the *Valkyrie* include spruce wood, and Mono-Kote.

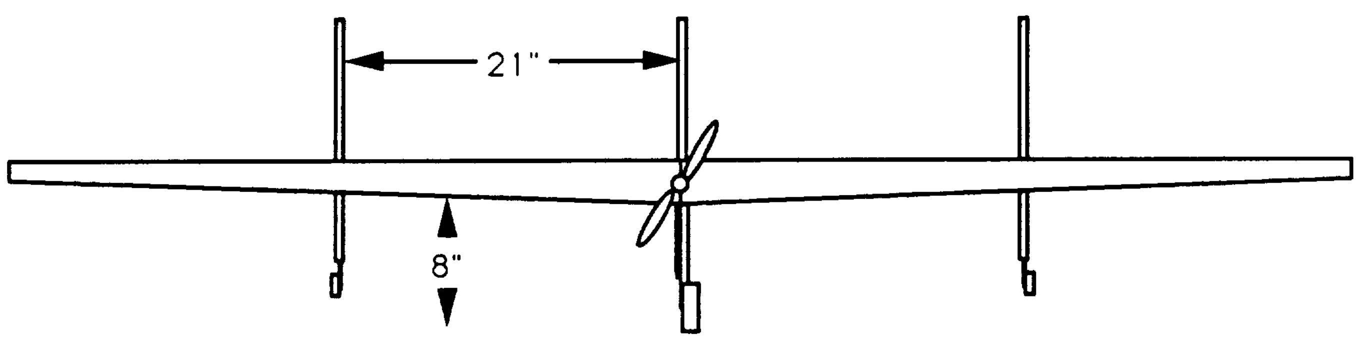
The *Valkyrie* is designed to take off in less than 20 ft. To eliminate the difficulties associated with rotating the aircraft at takeoff, the wing is mounted on its landing gear at the take off angle of attack of 8°. A velocity of 26.7 ft/sec is required

to generate enough lift to take off. Once airborne, the *Valkyrie* climbs to the cruise altitude of 20 ft, then flies at 32 ft/sec on a closed, figure 8 loop. In turns, the *Valkyrie* can either increase its speed or deflect it's control surfaces in order to maintain the cruise altitude. On landing, the aircraft must touch down at a speed of approximately 26 ft/sec to maintain trimmed conditions. The optimum glide path angle is –5.46°.

Finally, the *Valkyrie* provides a greater payload to weight ratio than a conventionally configured aircraft of comparable weight. Considering the requirements, the *Valkyrie* is the most efficient design for the specified mission.

Valkyrie





Nomenclature

AR	aspect ratio
b	wing span
c	chord
C_l	section lift coefficient
$C_{l\alpha}$	section lift slope
C_L	Valkyrie lift coefficient
C_d	section drag coefficient
C_{do}	section zero angle of attack drag coefficient
C_D	Valkyrie drag coefficient
C_{Do}	Valkyrie zero angle of attack drag coefficient
$C_{L\alpha v}$	lift curve slope of vertical stabilizer
$C_{L\alpha w}$	lift coefficint of wing
$C_{Lcruise}$	lift coefficient at cruise of aircraft
$C_{l\delta a}$	roll control power
$C_{L\delta e}$	Δlift due to elevator deflection
Cm_α	moment coefficient about cg
Cm_o	moment about cg at zero lift
Cn_β	yaw stability coefficient
c_{root}	root chord
e	span efficiency factor
E_m	max lift to drag ratio
i	current
I_x	moment of inertia about the x axis
J	propeller advance ratio
$L_{\delta a}$	roll moment due to aileron deflection
l_v	distance from cg to ac of vertical stab
mAh	milliamp hours
n	load factor
N.P.	neutral point
Q	dynamic pressure
RPM	revolutions per minute

S	planform area
S.M.	static margin
S_v	planform area of vertical stabilizer
t	time
TR	taper ratio
V	volts
V_{cruise}	cruise velocity
V_{stall}	stall velocity
V_{TO}	take-off velocity
V_v	verical tail volume ratio
V_∞	freestream velocity
α	angle of attack
α_{cruise}	angle of attack at cruise
α_{stall}	stall angle of attack
Γ	dihedral angle
Λ	sweep angle
δ_a	aileron deflection angle
δe_{cruise}	elevator deflection at cruise
η	propeller efficiency
η_v	dynamic pressure ratios
Φ	rolling angular acceleration
φ	bank angle
θ	bank angle
τ	control surface area ratio
ω	roll rate

Aerodynamics

$C_{L\alpha}$ =0.0624/degree
C_{Lo} = 0.0125
$\alpha_{L=0}$ = –0.2°
C_{Lmax} = 0.89
α_{stall} = 14°
$C_{Lcruise}$ = 0.42
L_{cruise} = 5.1 lbs
α_{cruise} = 6.5°
C_{Do} = 0.0237
$C_{Dcruise}$ = 0.037
D_{cruise} = 0.45 lbs
L/D_{cruise} = 11.33
L/D_{max} = 11.82
$\alpha_{L/Dmax}$ = 8.8°

Configuration

S (planform area)= 1440. in
b(wing span)= 84. in
Root Chord = 23. in
Tip Chord = 11. in
Γ(dihedral angle) = 2°
Λ(sweep angle) = 13.2°

Propulsion

1 Astro Cobalt 25 equipped with the Tornado 10-6 Propeller
-2 blades

Power Pack:

12 1.2 volt, 1. amp hour batteries yielding
15.42 volts of power

Cruise Conditions (Velocity=32 ft/s):

Voltage Setting: 6.3 volts
Current Draw: 4.24 amps
Prop RPM: 4668.4
Power Available: 21.2 watts
Thrust: 2.18 N
Prop Efficiency: 0.833
Max Range: 13,345 ft

Takeoff (maximum conditions, Voltage=15.42 volts)

Velocity Takeoff: 26.4 ft/s
Static Current Draw: 15.1 amps
Max Motor Power: 474.9 watts
Static Thrust: 3.9 lbs
Battery Drain: 5.7 mahs
Takeoff Distance: 16.8 ft

Static Prop RPM: 10. 467
Time: 1.35 seconds

Stability and Control Data Summary

Neutral Point: 0.373 of root chord
Static Margin: 9% mean chord/ 30% root chord
Cm_{α} -0.4
C_L cruise 0.42
α_{cruise} 8°
δ_{cruise} -8°
Elevator Area: 1.167 ft^2
Elevator Max. Deflection: -30° / +5°
$C_{L\delta e}$: 1.12
Vertical Tail Volume Ratio: 0.029
Vertical Stabilizer Area: 2 ft^2
Cn_{β}: 0.088
Rudder Area: 0.75 ft^2
Rudder Max Defection: ± 30°
Aileron Area: 0.817 ft^2
Aileron Max Deflection: ± 10°
$C_{l\delta a}$: -0.122

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2. *Introduction*

The following report and analysis proposes the development of a unique concept in air transportation. The *Valkyrie* system represents an attempt to isolate and dominate a specific consumer market by developing a new, innovative integration of existing technologies. This discussion seeks not only to examine and predict the performance characteristics of the final design, but, in addition to explore the analytical procedures, techniques and criterion which direct and influence the design process. The goal of this endeavor is to, not only understand the technical aspects of a specific design area, but more importantly to grasp some comprehension of the total design process and the "real world" parameters which govern the progress of technological development.

Section 3. Mission Assessment and Design Requirement Discussion

The *Valkyrie* flying wing will service the northern, central continent of Aeroworld. A demographic analysis of this continent suggests that a large volume aircraft is both necessary and ideal. Thus, as the DR&O states, the *Valkyrie* is designed to carry 100 passengers and it capable of servicing all but one route on the Northern Central continent. In order to accomplish this the *Valkyrie* has been designed to achieve a maximum range of 5600 ft which allow for service to all proposed routes, redirect, and loiter time if necessary. In addition, in order to most efficiently service these markets, the *Valkyrie* will travel at a speed of 32 ft/s (Mach=0.91) -see DR&O summary, section 4.

Market analysis of the passenger volume travelling between the cities of the northern, central continent suggests that there exists a lucrative market for a medium range, high volume aircraft. A high volume <u>commuter</u> aircraft provides several advantages. First, the large carrying capacity minimizes the total number of aircraft necessary to completely service the region. In comparison to smaller aircraft, the increased number of passengers allows for lower ticket prices and increased profits. In addition, total fleet maintenance costs are substantially reduced. Further, short flight times, those of less than an hour, allow a greater number of trips to be made per day, resulting in higher profits. Ticket pricing is equivalent to the ship fare which is $65.00 flat rate plus $0.16 per foot.

The maximum range of 5600 feet provides the *Valkyrie* with the ability to fly to its original destination, redirect to the nearest city, and loiter for one minute. The propulsion system selected for the *Valkyrie* has more than enough power to satisfy this requirement while still remaining highly fuel efficient (see section 11 for analysis and justification).

The only considerations limiting the size of the aircraft are a 7 ft wing span limitation and a volume requirement. The external configuration requires the use of three control surfaces: elevators, ailerons, and three vertical stabilizer/rudders. In addition, tricycle/tail dragger type landing gear will be employed. The landing gear will remain stationary (see DR&O summary in the following section).

The internal configuration of the aircraft must allow for comfortable seating of a minimum of one hundred passengers. Comfort and safety requires a minimum of 3/16 of an inch spacing between the passengers and an aisle, leading to an exit, for passenger access (see DR&O summary) There must also be room in the aircraft to accommodate the four servos, and their corresponding accessories, necessary to control the propulsion system and the control surfaces. The volume of the engine, receiver, batteries, and other components must be considered also. Providing sufficient space for all passengers and necessary components requires judicious selecting the wing's thickness, taper and sweep, as well as the internal structural configuration. As a result of the market evaluation, the combination of the relatively short routes between the cities on the northern central continent and its high passenger volume suggest that this is a very lucrative region. An efficient alternative means of travel, like the *Valkyrie,* would provide an innovative addition to the available forms of transportation.

Section 4. Design Requirement and Objectives Summary

The following listing provides a summary of the design requirements and objectives for the Valkyrie flying wing. Details pertaining to the information contained herein can be found in the subsequent sections. Please refer to the Table of Contents for assistance.

Aircraft Configuration:
- Large capacity aircraft (100 passengers)
- Maximum 84 in (7 ft) wingspan
- Planform area 1440 in^2 (10 ft^2)

Internal:
- Minimum 3/16 inch spacing between passengers (ping pong balls)
- Entrance/Exit Aisle
- Room to accomodate 4 servos, batteries, receiver, and engine

External:
- Three control surfaces: elevators, ailerons, and three stabilizer/rudders
- Tricycle/tail dragger landing gear (stationary)

Propulsion:
- A battery powered electric propulsion system capable of taking off while still maintaining a fuel efficient cruise condition

Performance:
- Maximum range of 5600 ft
- 32 ft/s cruise condition
- 16 ft/s R/C condition
- 286.7 ft/s takeoff speed
- 16.5 ft take-off distance
- 20 ft cruise altitude
- 25 ft absolute ceiling

Additional Requirements:
- Cooling (to avoid overheating)

Economic Analysis

Section 5. Economics

As the validation of the *Valkyrie* approaches, it is necessary to explain the economic feasibility of the overall flying wing design concept in terms of the costs, as well as the potential profit. The following section seeks to justify its production and operation.

5.1 Mission Requirement Cost Analysis

The mission requirements for the Aeroworld technology demonstrator required a mode of transportation that would be competitive with existing forms. A cost analysis was completed for the particular market that the *Valkyrie* seeks to dominate. This area encompasses the northern, central continent of Aeroworld and was chosen for its demographic characteristics. In addition, the analysis was determined based on an estimated weight of 5.02 lbs. for a 100 passenger aircraft and the maximum expected fuel costs for one day's continuous operation. Table 5.1, below, lists the routes that the aircraft would fly and the corresponding costs and profits involved. The study justified the claim that, in order to recover fuel and maintenance costs and to turn a sizable profit while remaining competitive, a large passenger aircraft was necessary.

A minimum of 90 passengers is needed to break even assuming that the fare charged is equivalent to that of the ship. As was previously mentioned, the population distribution of the northern, central continent is such that a 100 passenger aircraft is the most feasible. The merging of the innovative technical capabilities of the *Valkyrie* (100, that's over twice any of the competing designs) with the unique demographic characteristics of this market region provides and unprecedented opportunity for prodigious profit. This combination unquestionably makes the Valkyrie an economically efficient, high profile performer.

TABLE 5.1: Potential Maximum Passenger Daily Route

Flight	No. of Flights	Total Dist.	Ticket Revenue	Fuel Cost	Profit
		(ft)	per Flight ($)	per Flight ($)	per Flight ($)
J-K	10	8950	20,820	15,180	5,600
H-J	3	4026	27,940	22,300	5,630
G-H	5	6400	26,980	21,310	5,660
G-F	6	8484	29,120	23,450	5,670
G-J	1	2040	39,140	33,430	5,710
I-J	6	10250	33,840	28,150	5,690
F-J	2	4118	39,440	33,730	5,710
TOTALS	33	44270	923,000	736,000	187,000

Table 5.2 on the following page lists the suggested city to city routes that the *Valkyrie* should fly and their corresponding distances. Table 5.3 lists how much fuel is 'consumed' as well as the fuel costs associated with each flight. In addition, the ticket revenue per flight and the profit per flight can be seen in this table. The consumption of fuel, battery drain in milliamp hours, was determined using data obtained from the Fortran Take-off program and the TK!Solver Electric Performance program both available in the Notre Dame Aerospace Laboratory Computer Lab. Data from the take-off program showed that the 5.86 mAh were required. The battery capacity used during the cruise portion of the flight regime was dependent upon the flight time. An additional 1.9 mAh was assumed to have been drawn during taxiing. These values were used to determine the actual fuel consumed and the corresponding fuel cost for each flight. The $120/mAh maximum fuel cost was

the corresponding fuel cost for each flight. The \$120/mAh maximum fuel cost was used as a conservative estimate. Based on the values and a desired range of 5600 ft., it was determined that twelve, 1 amp hour batteries would meet the power requirements and still have additional power available.

5.2 Unit Production Cost

The projected production cost for one unit currently is estimated at a maximum value of \$115,400.00. After having manufactured the Technology Demostrator the actual retail cost of the aircraft was \$87,000. The price includes 273 man-hours for construction and approximately \$150 in materials. Efficient planning prior to construction may reduce the material required for the *Valkyrie* thus reducing the production cost. Based on the same rate for production, the cost of time and energy placed into the conceptual design of the *Valkyrie* is upwards of \$150,000.00. When determining the unit sale price, the above factors were taken into account as well as the potential savings in fuel costs and the revenue generated from ticket sales.

The propulsion system of the *Valkyrie* was selected in order to optimize 'fuel' savings. For this size and weight aircraft, the engine/propeller combination that was selected is the most efficient. As a result, fuel costs are kept to a minimum. Please refer to ***Section 11f*** or further details on the propulsion system. Ticket pricing is another attractive selling point of the *Valkyrie*. Calculations done on the proposed routes of the *Valkyrie* indicate that charging a minimum of \$0.17 per foot with no flat rate would be enough to recover the fuel costs. Considering that tickets must be priced in order to cover salaries and overhead, while at the same time ensuring that the airline remains very competitive, it is suggested that the fare for the *Valkyrie* be equivalent to that of the ship. This corresponds to a ticket price of \$65.00 flat rate plus \$8.00 per 50 ft. The distance rate is equivalent to \$0.16 per foot.

Table 5.3, on the previous page, lists the profit per flight of each of the suggested flights. This fare would be more than adequate to pay a two man crew a combined salary of approximately $130,000.00 per year as well as maintenance and other salaried employees. It remains up to the discretion of the airline to raise the ticket price. Considering the savings in time, it is certain that this price will be attractive to users of the other forms of transportation and that this will obtain their business.

Based upon these savings and the costs associated with design and construction, the unit sale price is approximately $750,000.00. This figure was achieved by summing all the expenses and multiplying this value by a factor of 3. This resulting value was then slightly reduced. The lower value makes the *Valkyrie* an even more fruitful prospect. With a fleet of *Valkyrie's* flying, it would not take long for the plane to pay for itself. As has been stated numerous times, the values presented in this document are conservative. The economic trend of the *Valkyrie* is that additional savings are certain to be realized.

The following section isolates those design driving parameters which continually re-emerged as the delineating constraints necessary to realize the economic possibilities of the*Valkyrie* air transportation concept.

TABLE 5.2: Distances between cities which provide service to over 400 passengers in ft.

City	A	B	F	G	I
A	0	1697.5	*	*	*
B	1697.5	0	*	2237	*
F	*	*	0	*	*
G	*	2236.5	*	0	*
I	*	*	*	*	0
J	*	4045	2059.5	*	*
K	*	4903.5	2953	*	2010
L	*	7026	*	*	*
M	*	*	*	*	*
N	*	*	*	*	*

City	J	K	L	M	N
A	*	*	*	*	*
B	4045	4904	7026	*	*
F	2060	2953	*	*	*
G	*	*	*	*	*
I	*	2010	*	*	*
J	0	895	*	*	*
K	895	0	2237	3256	3311
L	*	2237	0	*	1281
M	*	3256	*	0	*
N	*	3311	1281	*	0

TABLE 5.3: Possible Flight Routes

Flight	Distance (ft)	Flight Time (RW sec)	Fuel Consumed (mah)	Fuel Cost/Flight ($)	Ticket Rev/Flight ($)	Profit / Flight ($)
J-K	895	29.0	126.5	15,181.63	20,820.00	5,638.37
G-H	1280	41.0	177.6	21,317.57	26,980.00	5,662.43
H-J	1342	43.0	185.9	22,305.69	27,972.00	5,666.31
G-F	1414	45.2	195.4	23,453.19	29,124.00	5,670.81
I-J	1709	54.4	234.6	28,154.76	33,844.00	5,689.24
K-I	2010	63.8	274.6	32,951.94	38,660.00	5,708.06
H-I	2059	65.4	281.1	33,732.88	39,444.00	5,711.12
G-J	2040	64.8	278.6	33,430.07	39,140.00	5,709.93
F-J	2059	65.4	281.1	33,732.88	39,444.00	5,711.12
G-K	2800	88.5	379.5	45,542.57	51,300.00	5,757.43
F-I	2474	78.3	336.2	40,346.94	46,084.00	5,737.06

6. Design Drivers

Emphasized During Concept Selection

- Seating Capacity (goal set at 100)
- Fuel Efficiency (including both drag reduction and propulsive efficiency)
- Construction considerations (simplicity)

For Stability and Control

- Pitch stability
- Weight distribution -cg. placement

Aerodynamics and Configuration

- Moment Coefficient (C_{mo})
- Sufficient lift generation when trailing edge is reflexed
- Wing taper to position cg.

Propulsion

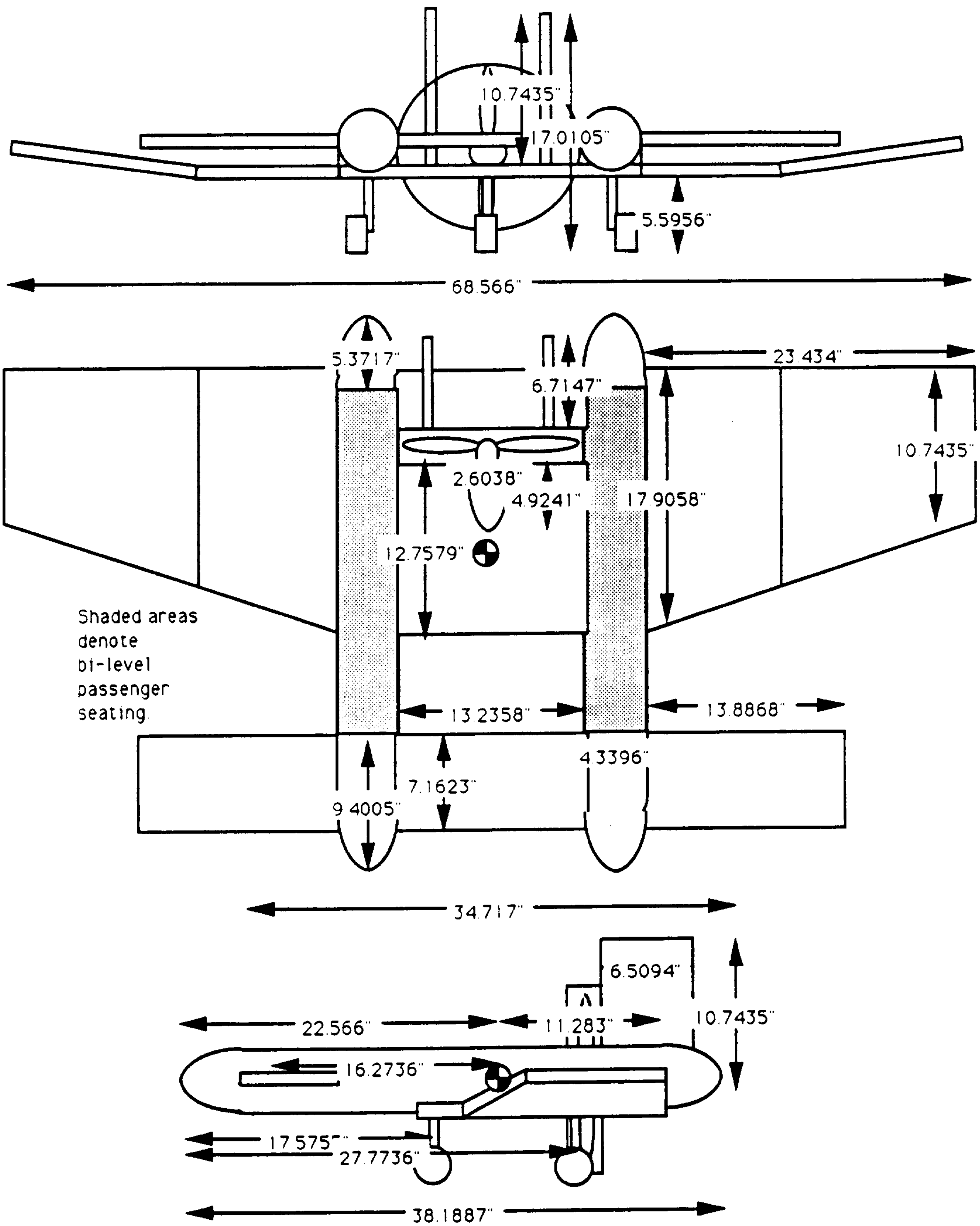
- Current draw at Cruise
- Sufficient power for takeoff considering reflexed trailing edge lift reduction
- Number of batteries required for takeoff

Structures

- Minimizing weight

The above parameters will continually re-emerge throughout the proceeding sections as the dynamic criteria driving the design process. This will most effectively illustrated in the following section which reviews the concept selection process that led to the *Valkyrie*.

Figure 7.1
Bustamante's Star Bus



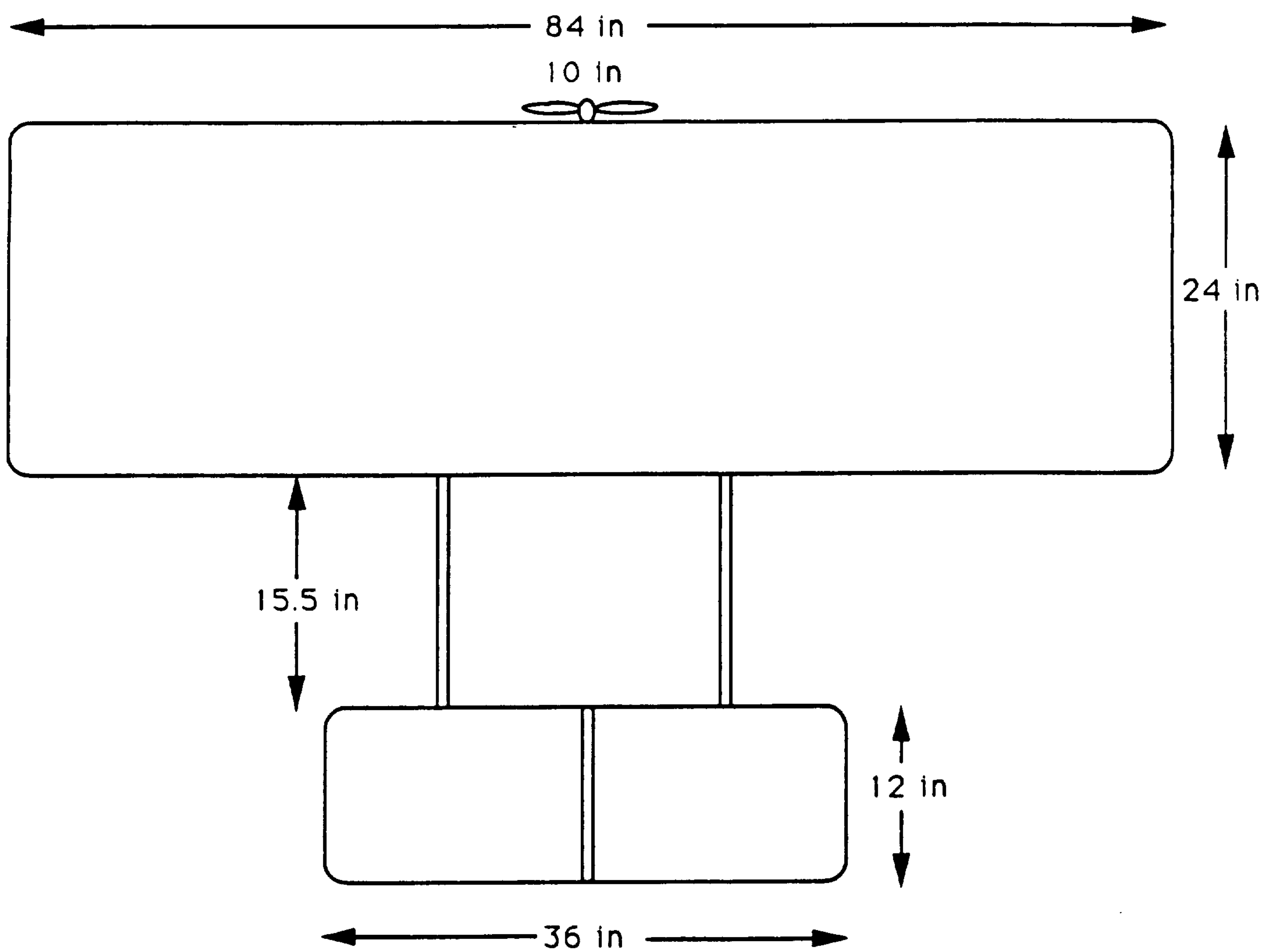
7. *Concept Selection*

The following section reviews and critiques a few of the competing design concepts in order to illustrate the strategy and criteria that most contributed to the overall selection process. This discussion primarily emphasizes three concepts: 1) the Bustamante twin fuselage Air Bus with counter rotating propellers, 2) a conventional aircraft with either a rear tail or a canard, and 3) the Henrich Hershey Bar Wing with vertical and horizontal rear stabilizers.

As evident from Economic analysis (section 5) and the Propulsion discussion (section 11), optimizing profit requires maximizing the aircraft's total passenger capacity (for a given market, see Mission Assessment), while simultaneously minimizing fuel costs. Assuming fuel costs, for purposes of this mission, are relatively fixed, reducing fuel consumption requires designers to minimize drag, and thus to prudently select an efficient engine-propeller combination. Each proposed preliminary concept sought to, in some fashion, incorporate these critical parameters into its conceptual development.

Figure 7.1 shows the Bustamante twin fuselage Air Bus with counter rotating propellers. Unquestionably, this design demonstrates some important characteristics: 1) it possesses a passenger capacity capable of comfortably seating 100; 2) it's innovative; and 3) the separated twin fuselages effectively supply the propeller with a uniform, uninterrupted air flow which increases the propeller's overall efficiency (no large structure to interfere with the flow). The degree of innovation required by this concept was even more than the courageous group Zeta dared to challenge. The logistics of installing two engines, face to face, with synchronous counter rotating propellers, and an inherent possibility for thrust vectoring, generated

Figure 7.2
Henrich's Hershey Bar Wing



morbid fear and terrified uncertainty amongst many of the team's most prominent members. Moreover, although having 2 fuselages reduces the interference with the propeller's air flow, these large structures would still generate a significant drag penalty. Finally, viewing this from a practical perspective, building two separate fuselages, then mounting 2 engines between them could prove extremely, even excessively, challenging.

Another designs, suggested by Marty, Bob, Steve and Pat, resemble more convention aircraft, except each employs some configurational variation, such as canards or pusher propellers. These proposed designs, by one means or other, managed to seat roughly 100 passengers (seating 100 people quickly emerged as a primary configurational consideration after Zeta finished assessing the economics of their mission). In each instance, regardless of any individual variations, the fuselage -required to seat 100 people- became so large that the propeller interference and drag generated by this structure proved intolerable. The only advantage to more conventional concepts is the availability of analytical techniques and the considerable size of the accessible data base (that is, it has been done many times before)

Lastly, Henrich's Hershey Bar Wing was reviewed (Fig. 7.2). Removing the fuselage entirely both significantly reduces the propeller interference as well as the overall drag (note, obviously the fuselage accounts for a preponderance of the total drag; this concept has no fuselage). The large interior volume of the wing provides more than sufficient room to comfortably seat 100 passengers. The rear vertical and horizontal tails, placed out on booms, supply ample stability and control, parameters which are often problematic in flying wing concepts. Finally, a single long wing of uniform chord is by far the simplest of the designs to construct.

Eventually the notion of eliminating the problematic fuselage and

seating the passengers in the wing began to make more and more sense. The wings of the other concepts were roughly the same size as the Hershey Bar wing, and were, in themselves, large enough to seat a sufficient number of passengers. Further research into flying wing designs revealed that the horizontal tail could be replaced by employing a reflexed tailing edge on the main wing, provided the configuration was tapered to allow a larger moment arm at the trailing edge. Thus, the Valkyrie was born.

The proceeding section initiates an extensive, in depth discussion of all the *Valkyrie's* critical areas, beginning with the Aircraft Configuration and Aerodynamics. Many of the decisive parameters indicated above will continue to re-emerge as fundamental guidelines for further design alterations and improvements.

Aerodynamics

Section 8. Aerodynamics

8.1 Planform Configuration

Several design parameters, including internal wing volume, adequate stability and control, and sufficient lift during all phases of flight, determined the planform design of the *Valkyrie*. The following section seeks to explain the advantages of the present planform design of the *Valkyrie*. The reader is asked to refer to the other sections for a more thorough explanation of the statements contained herein.

The main factor in selecting the flying wing design was the concept's excellent payload to aircraft weight ratio. The driving design goal was to carry 100 people in the aircraft. In order to achieve enough lift to carry 100 passengers, the calculated wing area was rather large (10 square feet) with respect to previous RPV designs. The wing is large enough such that adequate space exists inside the wing to house passengers, control mechanisms, and fuel.

The next step was to define the planform geometry. A tapered wing seemed the best choice for a number of reasons. First, it has a better efficiency factor, e=0.86 in this case, than does an untapered, rectangular wing. The lift distribution of a tapered wing more closely resembles the lift distribution of an elliptic planform, which represents the most efficient planform. Due to construction difficulties the elliptic planform was ruled out as a choice for the wing. Therefore, the tapered wing configuration represents a tradeoff between efficiency and ease of construction. Though producing more induced drag than the optimal elliptic wing, the tapered wing creates less induced drag than a rectangular wing, which is the simplest wing to construct. The tapered wing geometry also allows for increased stability and control because it has a larger static margin (distance between center of gravity and center of pressure) than a rectangular wing.

The roll stability of the aircraft is of significant importance since the majority of the flight evaluation testing will subject the technology demonstrator to turning flight. The *Valkyrie* employs a leading edge sweep of approximately 13.2° which produces a dihedral effect that aids in roll stability. In addition, a dihedral angle of approximately 2° is built into the aircraft. Note that the percentage thickness, t/c, of the wing across the span will not change, but the chord length does change. The wing is straight across the top, which results in a change in chord thickness across the span from the root to the tip of the wing relative to the top surface. This provides for a dihedral angle. Please refer to the 3–view drawing of the aircraft at the beginning of this document for a graphic representation of the dihedral angle.

As with most wing designs, the goal is to choose a planform which provides the best lift with the least amount of drag. In order to determine the optimum taper ratio for our wing, the program LinAir was used. A parametric trade study was performed which investigated the effects of varying the taper ratio and dihedral angle. However, some important parameters had to be determined before accomplishing this study. The planform area had to be known in order for the prospective payload capacity to be met. A span was chosen that would allow the aircraft to fit into only the largest terminals in Aeroworld, since these destinations provide the greatest profit for our payload capabilities. Based on accepted airfoil data for the NACA $2R_2 12$, the necessary cruise lift can be achieved at a 6.5° angle of attack. See the second section following and Figure 8.3 for a more thorough discussion of airfoil aerodynamics.

The trade study involved varying the dihedral angle between 0° to 4°, and the taper ratio from 0.3 to 0.8. In the final analysis, the optimal lift to drag combination was found for a planform with a dihedral of 2° and a taper ratio of 0.5. As a result of the change thickness of the airfoil, the Valkyrie in fact has a built–in 2° dihedral. Table 8.1 lists the important planform results.

Table 8.1Planform Geometry

S (planform area)	1440 in.2 (10 ft.2)
b (wing span)	84 in. (7 ft.)
Root Chord	23 in.
Tip Chord	11 in.
Taper Ratio	0.48
Γ (dihedral angle)	2°
Λ (sweep angle)	13.2°
V_v (vertical tail volume ratio)	0.029

The values listed above are the actual dimensions for the completed *Valkyrie*. Subsequent sections will cite these numbers in greater detail.

8.2 Airfoil Selection

Several important design parameters influenced the airfoil selection process for the *Valkyrie*. Though selection of the proper wing airfoil section represents an important milestone in the design of any aircraft, the process is absolutely critical for the flying-wing configuration. While parameters such as adequate lift curve slope, high C_{Lmax}, and small C_{do} influence the airfoil selection of most aircraft, additional structural and stability requirements affect the airfoil selection process for the flying-wing design. One of the primary considerations in the design of the *Valkyrie* was adequate pitch stability and control since the flying wing configuration lacks a horizontal tail with which to provide these requirements; therefore, the selected airfoil had to have a minimum moment coefficient about the quarter chord. In order to reduce as much as possible any undesirable pitching moment about the c.g. of the aircraft, caused by the unequal

Figure 8.1
NACA 2R212 Airfoil

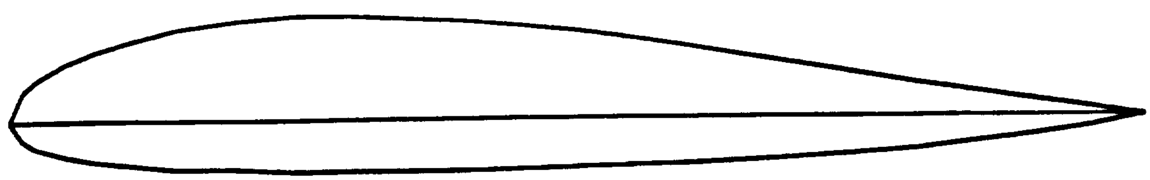
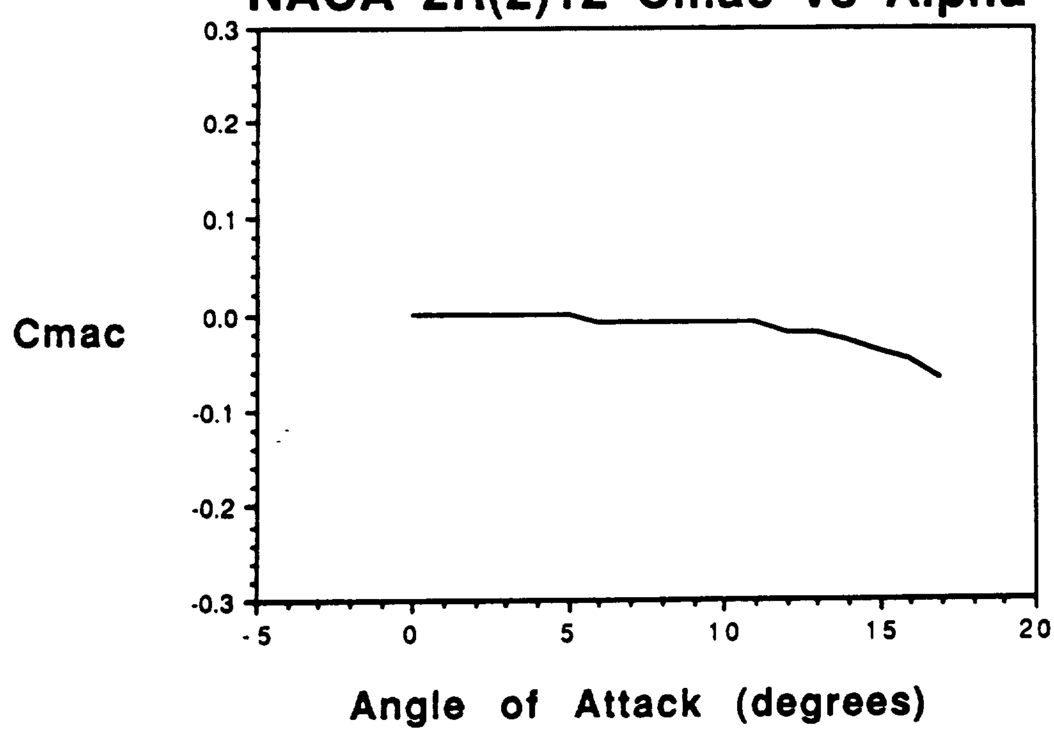


Figure 8.2
NACA 2R(2)12 Cmac vs Alpha

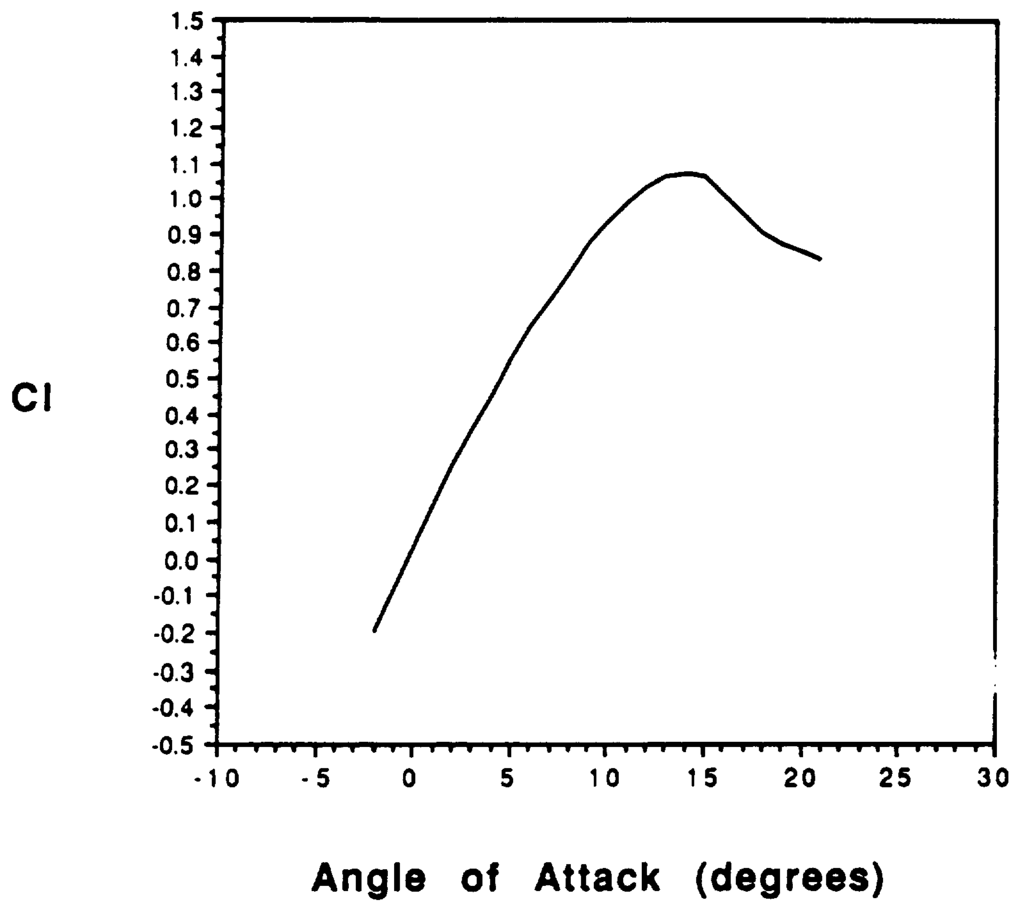


pressure distribution over the surface of the wing, the NACA $2R_2 12$ airfoil was chosen for the wing airfoil section. See Figure 8.1. This particular airfoil has a 2° upward reflexed trailing edge which balances the negative, pitch down, moment coefficient about the aerodynamic center, C_{mac}, arising from the pressure distribution over the airfoil.

As Figure 8.2 illustrates, for reasonable angles of attack up to approximately 11° the C_{mac} never drops below -0.01. Even at large angles of attack beyond α_{stall} (14°) the C_{mac} of the airfoil never exceeds -0.07 This relatively small airfoil pitching moment coefficient is a desirable characteristic for the flying wing design. The NACA 4412 airfoil was originally considered for the design, as it produces adequate lift during all stages of flight. However, with a C_{mac} of approximately –0.10, the 4412 violates the small C_{mac} requirement. This value was considered too high to ensure adequate pitch stability and control.

The maximum thickness of the airfoil in percent chord, t/c, is another important aspect of airfoil selection. Since the *Valkyrie* will carry all passengers, fuel, and control mechanisms within its wing, adequate wing volume—a function of airfoil thickness—is crucial to the success of the flying wing. The $2R_2 12$ has a maximum thickness of 12% chord, which provides the structures group with adequate usable volume for safe and comfortable passenger placement as well as propulsion and control system housing. Thicker derivative airfoils, such as the $2R_2 15$ and $2R_2 18$, were considered, but the larger parasite drag coefficients associated with these sections made them undesirable for the flying wing design. The $2R_2 12$ also has concave–out surfaces and no sharp edges, and thus should not prove extremely difficult to construct.

Figure 8.3
NACA 2R(2)12 Lift Curve



8.3 Airfoil Aerodynamics

In addition to the $C_{mac} \approx 0$ requirement, the selected airfoil has to meet several other requirements. First, the selected airfoil must have an adequate lift curve slope to provide the required C_l at an α_{trim} well below α_{stall} so the aircraft will not stall in case it experiences a sudden gust or other atmospheric anomaly which pitches it to a high angle of attack. Secondly, the airfoil should have a sufficiently small parasite drag coefficient to reduce as much as possible the power required to propel the aircraft. The NACA $2R_212$ meets both of these requirements. Figure 8.3 shows the experimental lift curve for the NACA $2R_212$, taken from documented, experimental data. A cruise velocity of 32 ft/sec (from power requirements) and an expected air temperature of 25 °C give an average cruise Reynolds number for the *Valkyrie* of approximately 287,000. Note that, since the chord length of the wing varies across the span, the Reynolds number also changes along the span. The maximum Reynolds number of 388,000 occurs at the wing root, while the wing tip encounters the minimum Reynolds number of 186,000. The experimental data shown in Figure 8.3 was taken at a Reynolds number of 300,000, which closely matches the average cruise Reynolds number of 287,000. Though no experimental data for this exact Reynolds was available, the data shown in Figure 8.3 provides a very close approximation of the expected lift of the average chord length airfoil, since experimental lift data varies little at low Reynolds numbers below the stall angle of attack for the NACA $2R_212$.

Figure 8.3 indicates a lift curve slope of approximately 0.086 per degree (4.93 per rad), a lift coefficient at zero angle of attack, C_{lo}, of 0.02, and an angle of attack at zero lift of -0.2°. The maximum lift coefficient of 1.07 occurs at a stall angle of attack of 14°. Note that the airfoil stalls gradually over a 3 or 4° angle of attack range, and never stalls abruptly. Note also that the airfoil has a smaller lift curve slope and C_{lmax} than similar airfoils without reflexed trailing edges. The reflexed trailing edge

Figure 8.4
NACA 2R(2)12 Drag Polar

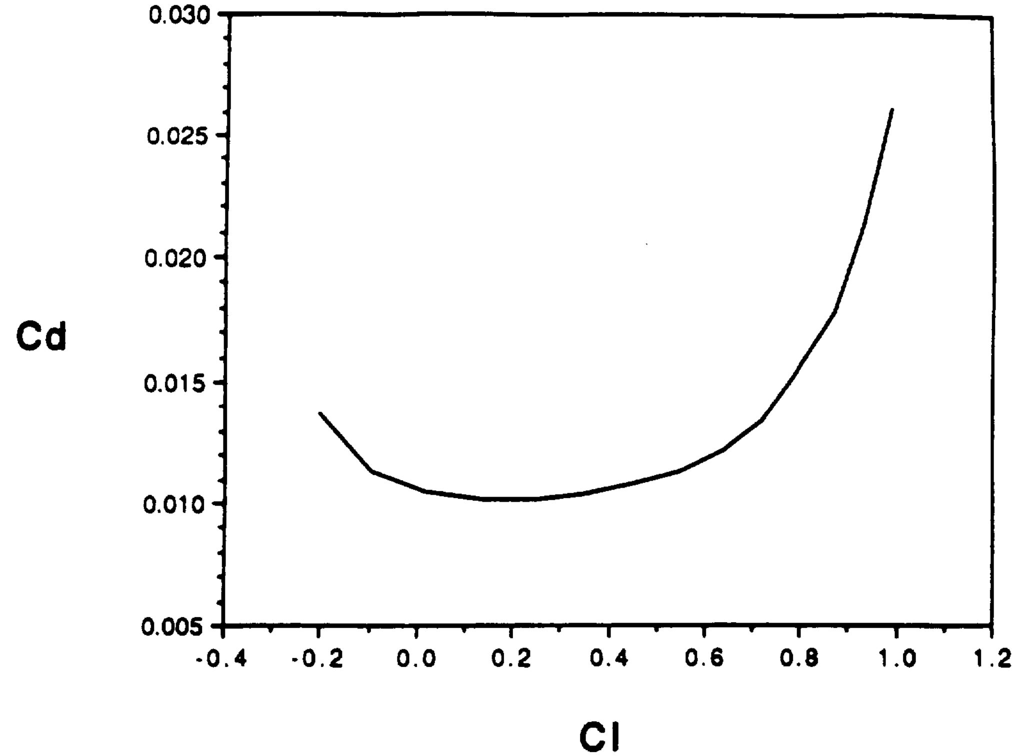
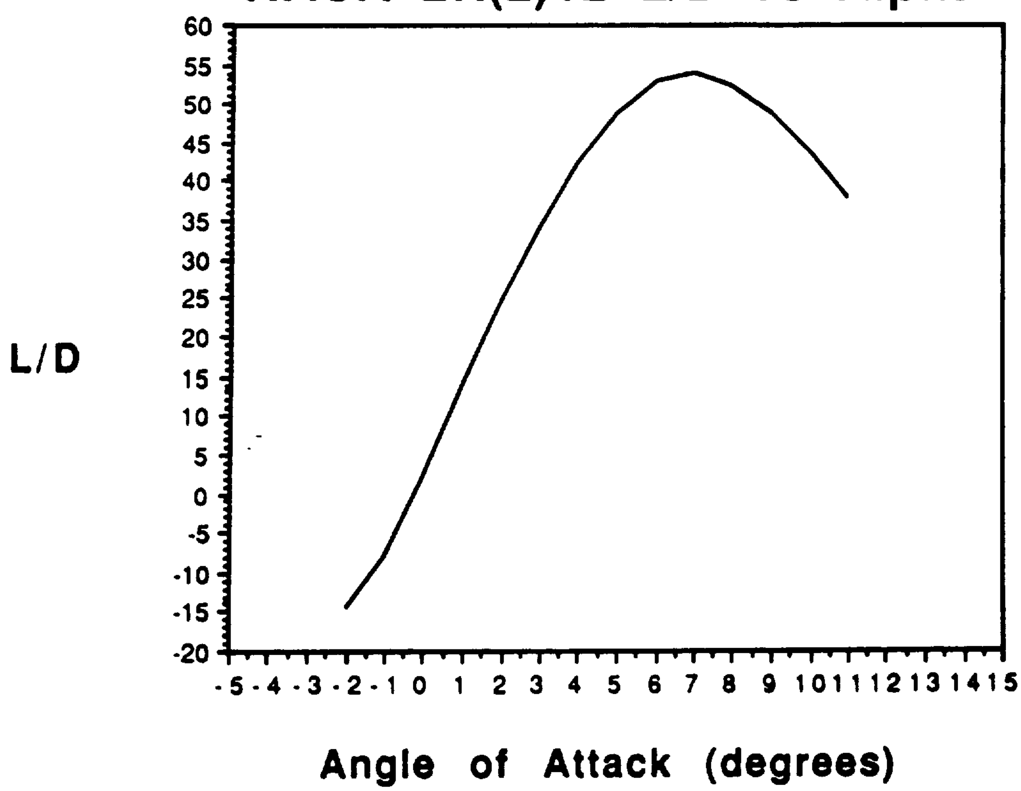


Figure 8.5
NACA 2R(2)12 L/D vs Alpha



produces a slight download on the airfoil near its trailing edge which has a detrimental effect on the overall lift produced by the airfoil at a given angle of attack. As this same download also negates the moment coefficient, a tradeoff must be made between decreasing the lift slope of the airfoil, an undesirable effect, and reducing the pitching moment coefficient of the airfoil, a desirable effect. Even though cancelling the C_{mac} of the airfoil means reducing its effective lift curve, adequate lift for the aircraft as a whole can be achieved by flying at higher speeds and/or flying at slightly higher angles of attack. Unfortunately, both of these methods involve increasing the overall drag of the aircraft, as will be discussed later.

Figure 8.4 shows the drag polar for the NACA $2R_2 12$, reproduced from documented, experimental data. As expected, the drag coefficient, C_d, varies quadratically with C_l. The airfoil displays a parasite drag coefficient, C_{do}, of approximately 0.01 when $C_l=0$. This is the minimum value of C_d. The parasite drag coefficient meets the requirement for a small C_{do}.

Figure 8.5 illustrates the Lift to Drag ratio, L/D, characteristics of the airfoil. This plot indicates that at an angle of attack of approximately 7.5°, the airfoil achieves a maximum L/D of about 53.

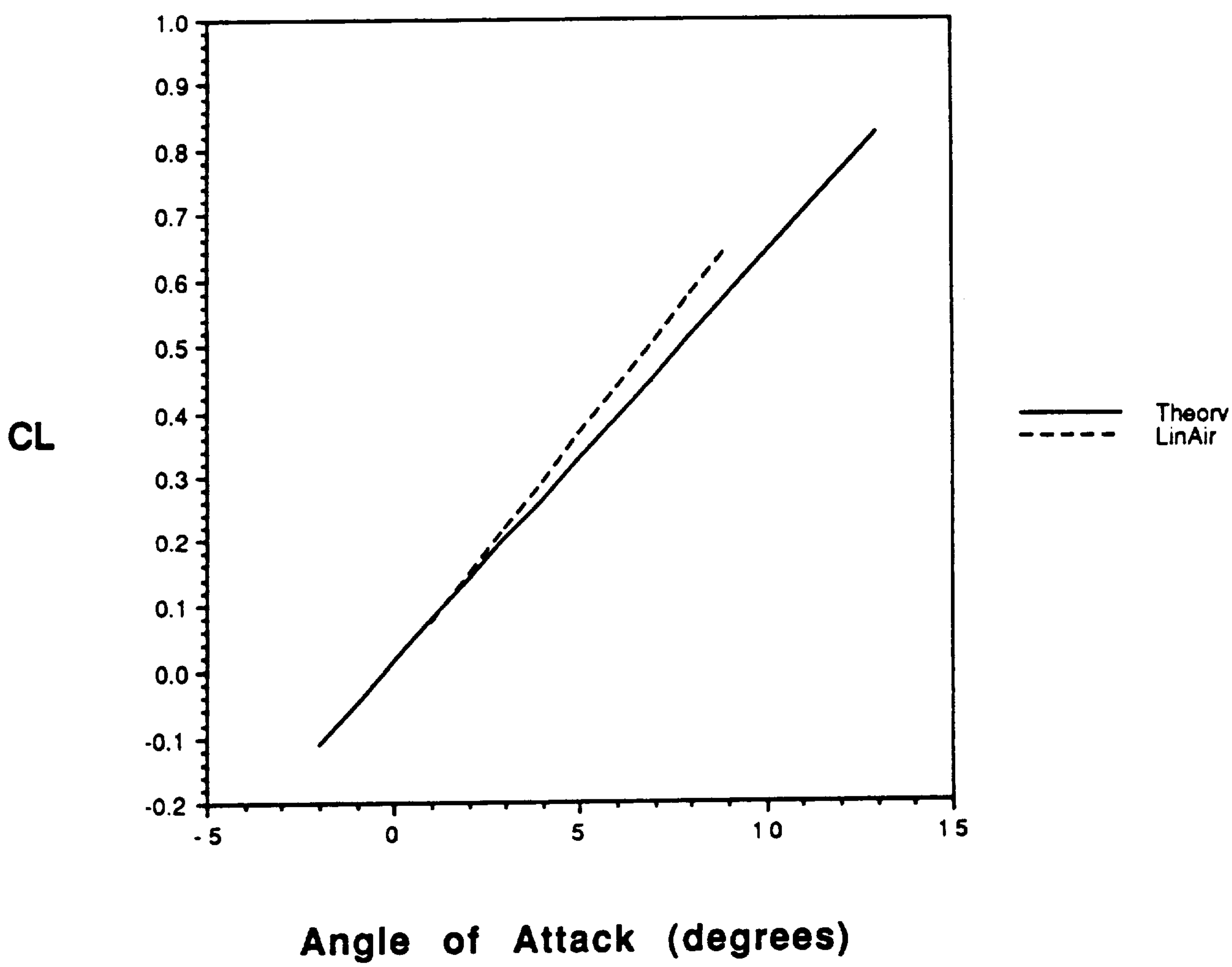
8.4 Aircraft Aerodynamics

Accurate prediction of the aircraft aerodynamic characteristics requires calculation of the overall Oswald efficiency factor, e. The efficiency factor for the clean aircraft (i.e., flaps up) was estimated using the equation:

$$1/e = 1/e_{wing} + 1/e_{fuselage} + 1/e_{other}$$

where the wing contribution was determined, using the design aspect ratio of 4.9, from design charts as approximately 0.9. As the *Valkyrie* flying wing design does

Figure 8.6
Valkyrie Lift Curve



not include a fuselage, the fuselage term was neglected in the calculation. Finally, a value of 0.05 provides an estimation for the $1/e_{other}$ term. The above equation provided a value of 0.86 for the overall efficiency, e, of the aircraft. The *Valkyrie* has a relatively high efficiency because it lacks an efficiency-reducing fuselage, and this high efficiency represents a major advantage of the flying wing design.

As the next group of plots illustrate, the*Valkyrie* aircraft displays much different aerodynamic characteristics than the NACA $2R_2 12$ airfoil section. Figure 8.6 shows the theoretical lift curve calculated from airfoil theory. Using the known airfoil lift curve slope (0.086 per degree), the wing aspect ratio (4.9), and the calculated Oswald efficiency factor (0.86), the lift curve slope for the wing (and in this case, for the entire aircraft) can be calculated from

$$C_{L\alpha} = C_{l\alpha}/(1+C_{l\alpha}/\pi ARe)$$

and the lift curve generated using

$$C_L = C_{L\alpha}(\alpha-\alpha_{l=0})$$

where $\alpha_{l=0}$ is the same as that for the airfoil (–0.2°). The lift curve plot indicates a lift curve slope of approximately 0.0624 per degree and a C_{Lmax} of 0.824 per degree at the stall angle of attack of 13°. The stall angle of attack was estimated using a commercial, lifting line theory computer program call LinAir. Though the program cannot actually predict stall, the stall angle of attack may be determined by monitoring the lift coefficient distribution across the span of the wing over a high angle of attack range. When the program delivers a C_l anywhere across the span greater than the C_{Lmax} of the airfoil, stall has probably been reached. According to LinAir, the *Valkyrie* begins to stall at approximately 13°.

Figure 8.7
Valkyrie Lift Distribution

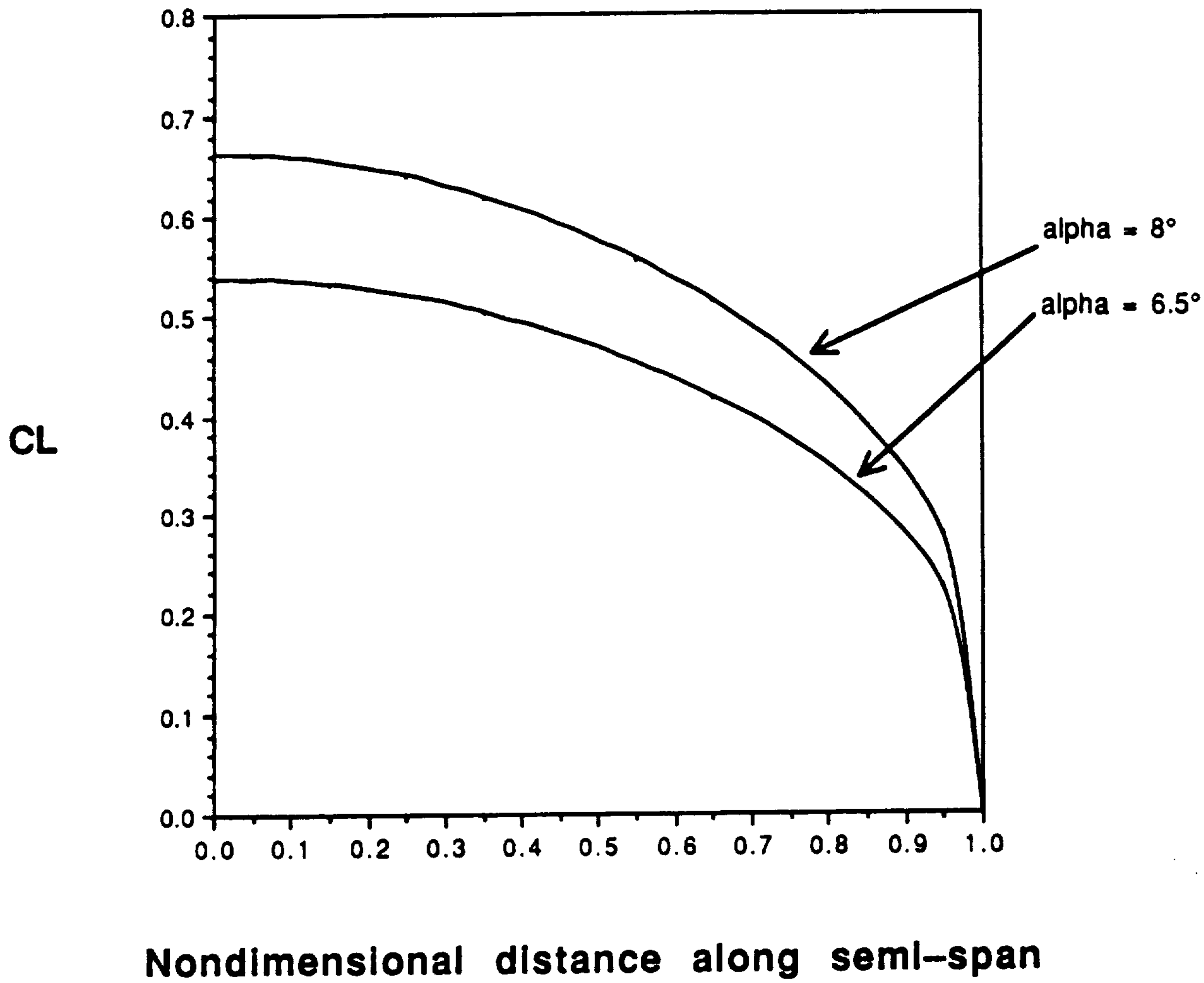
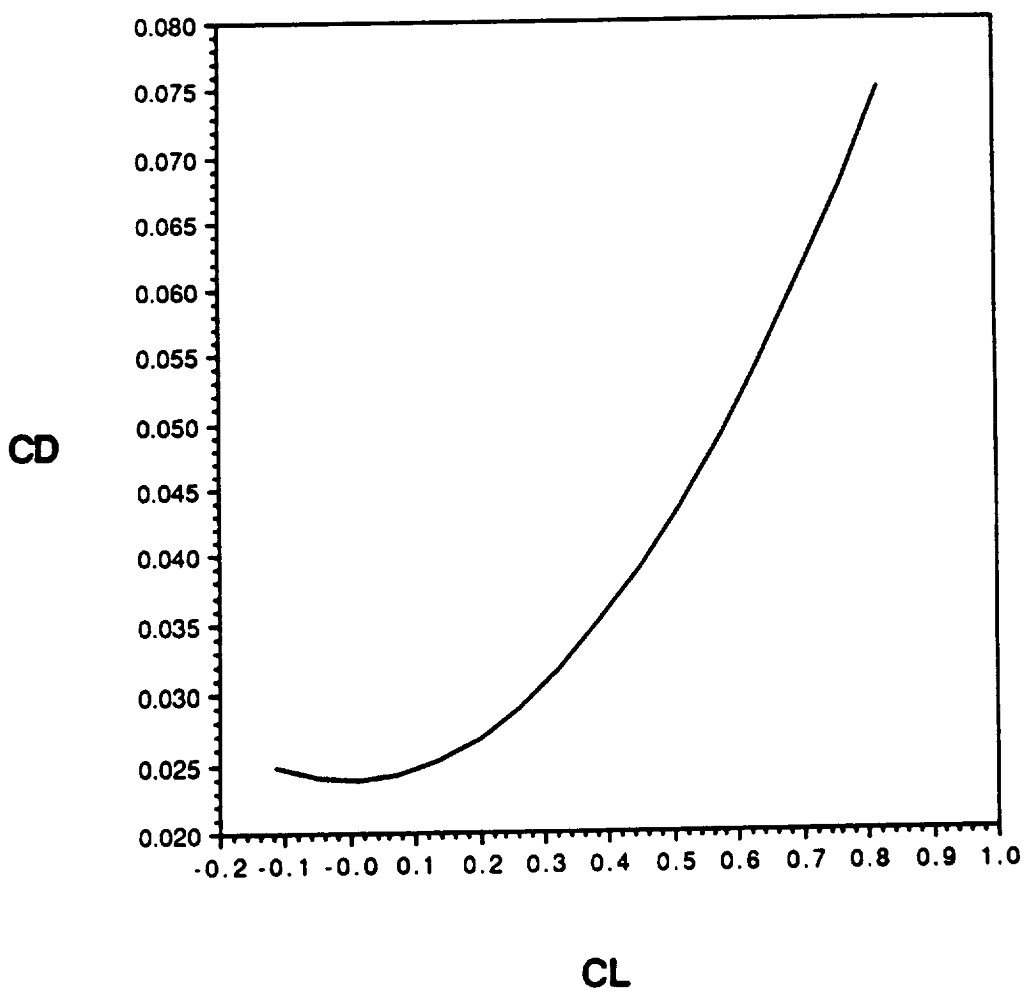


Figure 8.6 also indicates that the lift coefficient at zero angle of attack, C_{l_0}, is 0.0125. Note that all the preceding parameters seem relatively small because they all depend, in one way or another, on the lift curve characteristics of the airfoil, which has a reduced lift curve because of the airfoil's lift–reducing reflexed trailing edge. Thus, the aircraft lift curve and associated parameters are similarly reduced. Finally, the plot also shows the lift curve, over a 1° to 9° angle of attack range, for the *Valkyrie* predicted by LinAir. LinAir calculates a lift curve slope of 0.0716 per degree for the aircraft. Thus, the two methods correspond rather well. However, all subsequent calculations were done in a conservative fashion, utilizing the smaller value for the lift curve slope.

Assuming a steady, level cruise at a velocity of 32 ft/sec gives a required cruise C_L of approximately 0.42. This lift coefficient can be achieved at a 6.5° angle of attack. In order to trim the airfoil, however, a –8° elevator deflection is required. This upward deflection reduces the effective lift produced by the wing, and the aircraft must therefore be pitched to a higher angle of attack in order to achieve the required lift for steady, level, trimmed flight. An 8° angle of attack in combination with a –8° elevator deflection meets the cruise requirement. Thus, the *Valkyrie* will cruise at an 8° angle of attack with an –8° elevator deflection. This configuration satisfies the trim requirement as well as the steady, level cruise requirement, and also provides a lift coefficient of 0.42. The trim requirement and condition will be discussed further in the *Stability and Control* section.

Figure 8.7 shows the lift distribution across the semi–span of the wing at two angles of attack, as calculated by LinAir. Recall that a 6.5° angle of attack provides adequate lift (C_L = 0.42) to cruise at a velocity of 32 ft/sec, but that an angle of attack of 8° (in combination with an –8° elevator deflection) is required to trim the aircraft at cruise (see *Stability and Control* for further details). As expected, the lift coefficient for the 8° angle of attack is larger at every station along the wing than for

Figure 8.8
Valkyrie Drag Polar



the 6.5° angle of attack. Note that the lift distribution roughly approximates that of an elliptic distribution, and the *Valkyrie's* tapered wing more closely approximates the optimally efficient elliptic wing planform than would a simple rectangular wing. Thus, the tapered main wing creates less induced drag than would a rectangular wing. Finally, note that as LinAir only calculates the lift distribution over a part of the span, the lift distribution for the initial and final 5% of the span has been interpolated.

8.5 Drag Prediction

Accurate prediction of the total drag produced by the aircraft is an important procedure for determining both the aerodynamic performance of the aircraft and the power required during all phases of flight. In order to obtain a high degree of accuracy, several methods were used to estimate the parasite drag. A two parameter equation was assumed to for the drag polar of the *Valkyrie*.

Figure 8.8 shows the drag polar for the *Valkyrie*. This plot was generated using the equation

$$C_D = C_{D_0} + \frac{C_L^2}{\pi A R e}$$

where the parasite drag coefficient, C_{D_0}, is approximately 0.0237, and corresponds to the C_D where the lift coefficient equals zero. As expected, the total drag coefficient grows parabolically with increasing lift coefficient. At the cruise condition (C_L=0.42), the drag coefficient is approximately 0.037, as shown on the graph. The parasite drag coefficient was calculated using the component build-up method. This method involves calculating the drag coefficient contribution from individual components based on a certain reference area, then summing the individual contributions to

obtain the overall C_{Do} for the aircraft. For the *Valkyrie,* the individual components contributing to the overall parasite drag include the wing structure, the vertical stabilizers, and the landing gear. Note that the *Valkyrie* suffers no drag penalties from either a fuselage or a horizontal tail, and therefore has a smaller total parasite drag coefficient than conventional designs. Lower parasite drag is another advantage of the flying wing design. Using the equation

$$C_{Do} = (\Sigma C_{D\pi} A_{\pi})/S_{ref}$$

where $C_{D\pi}$ represents the component drag coefficient, A_{π} is the area upon which $C_{D\pi}$ is based and S_{ref} corresponds to the wing planform area of 10 ft^2, gives a C_{Do} of approximately 0.0235. This value includes parasite drag contributions from the wing, landing gear, vertical tails, and 10% increase for skin roughness effects. Table 8.2 provides details on the component breakdown method.

Table 8.2 Drag Breakdown

Component	C_{Do}
Wing	0.0070
Vertical Tails (3)	0.0016
10% increase for roughness	0.10*0.0086=0.00086
Landing Gear	0.0140
–8° cruise flap deflection	0.0027
Total	0.0262

The LinAir program gave a close correlation of 0.0236 for C_{Do}. This correlation gave reliability to the LinAir program for drag estimation, which was therefore used to calculate the change in C_{Do} with an elevator deflection. Since the *Valkyrie* cruises with an elevator deflection of –8°, determining the drag increase caused by this deflection seemed important for power considerations. Figure 8.9

Figure 8.9
Variation of CDo with Elevator Deflection

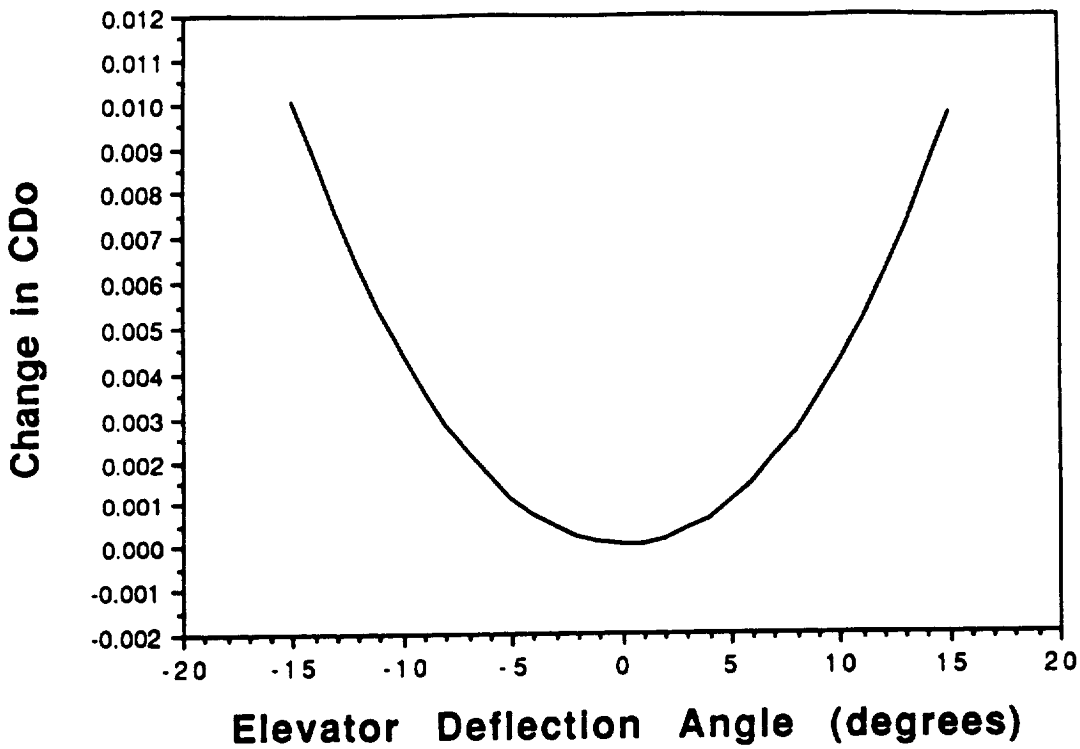
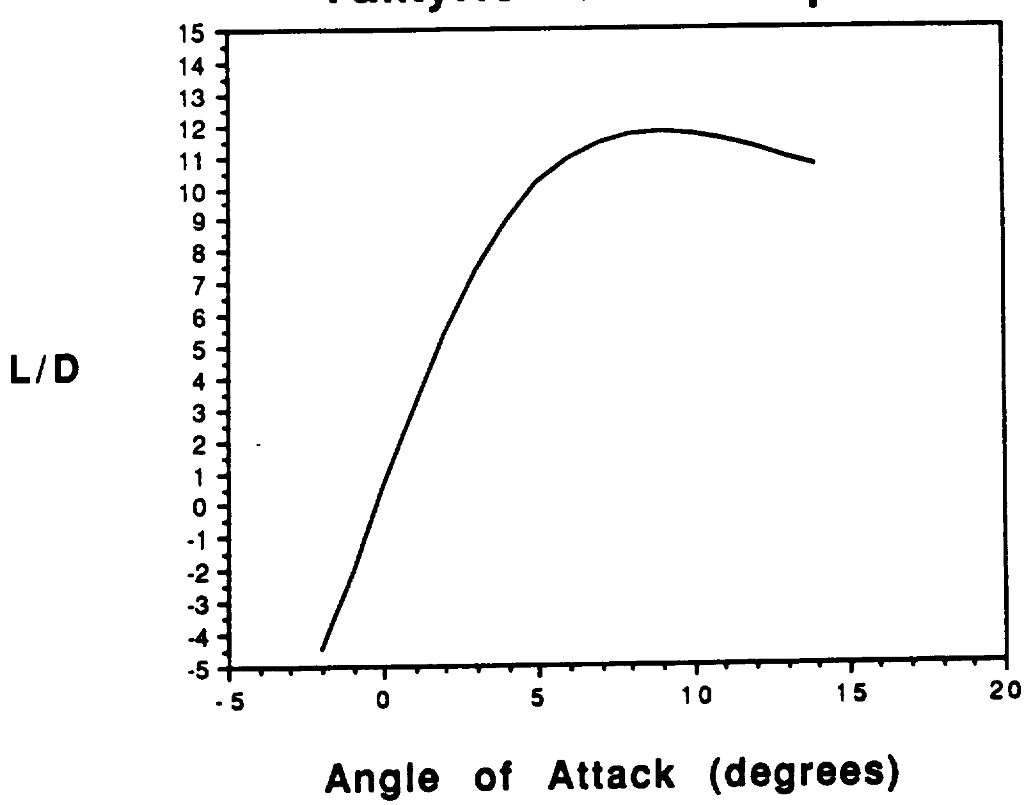


Figure 8.10
Valkyrie L/D vs Alpha



shows the *change* in C_{Do} with respect to the clean configuration (no elevator deflection) over an elevator deflection range of +15° to −15°. The graph displays near perfect symmetry about the vertical axis, and curve fitting the data results in an exact parabola of the form

$$\Delta C_{Do} = -4.3907e\text{-}5 - 1.0589e\text{-}5*(\delta) + 4.3855e\text{-}5*(\delta)^2$$

where δ is the elevator deflection angle in degrees. An elevator deflection angle of −8° increases the parasite drag coefficient by an additional 0.0027, as indicated in Table 8.2, bringing the total C_{Do} at cruise to 0.0262.

In the cruise configuration with an angle of attack of 8° and an elevator deflection of −8°, the total drag coefficient, including parasite drag and induced drag, was estimated by LinAir to be approximately 0.05, corresponding to a total drag at cruise of 0.61 lbs. Note that at the cruise configuration, the parasite drag contribution dominates the induced drag contribution, thus emphasizing the importance of accurate C_{Do} prediction.

Finally, Figure 8.10 shows the lift to drag versus angle of attack characteristics for the *Valkyrie*. The parameter L/D reaches a maximum value of 11.82 at an angle of attack of 8.8°. Note that, because of the reduction in lift curve slope by finite aspect ratio and non–elliptic wing, and the induced drag created by the wing, this value is much smaller than the maximum lift to drag ratio for the airfoil. Cruising at a C_L of 0.42 and a C_D of 0.05, the *Valkyrie* achieves a lift to drag ratio 8.4. Table 8.3 provides a summary of all important aerodynamic data for the *Valkyrie*.

Table 8.3	
$C_{L\alpha}$	0.0624/degree
C_{Lo}	0.0125/deg
$\alpha_{L=0}$	-0.2°
C_{Lmax}	0.82
α_{stall}	13°
$C_{Lcruise}$	0.42
L_{cruise}	5.1 lbs
α_{cruise}	8°
C_{Do} (clean)	0.0237
$C_{Dcruise}$	0.05
D_{cruise}	0.61 lbs
L/D_{cruise}	8.4
L/D_{max}	11.82
$\alpha_{L/Dmax}$	8.8°

Having examined the aerodynamic characteristics of both the NACA $2R_2 12$ airfoil and the *Valkyrie* flying wing, the analysis now proceeds to the *Structures and Payload* section, which investigates the relationship between internal structure and planform and airfoil geometry.

Structures and Payload

Section 9. Structures and Payload

9.1 Loading:

For the purposes of this proposal the term loading environment will include both the limit loads imposed upon the structure of the *Valkyrie* as well as the specific loading features of this unique aircraft. While it would be possible to explain all the possible in-flight loading situations that the *Valkyrie* might be exposed to, this data can best be presented by the V-n diagram for this aircraft (See figure 9.1).

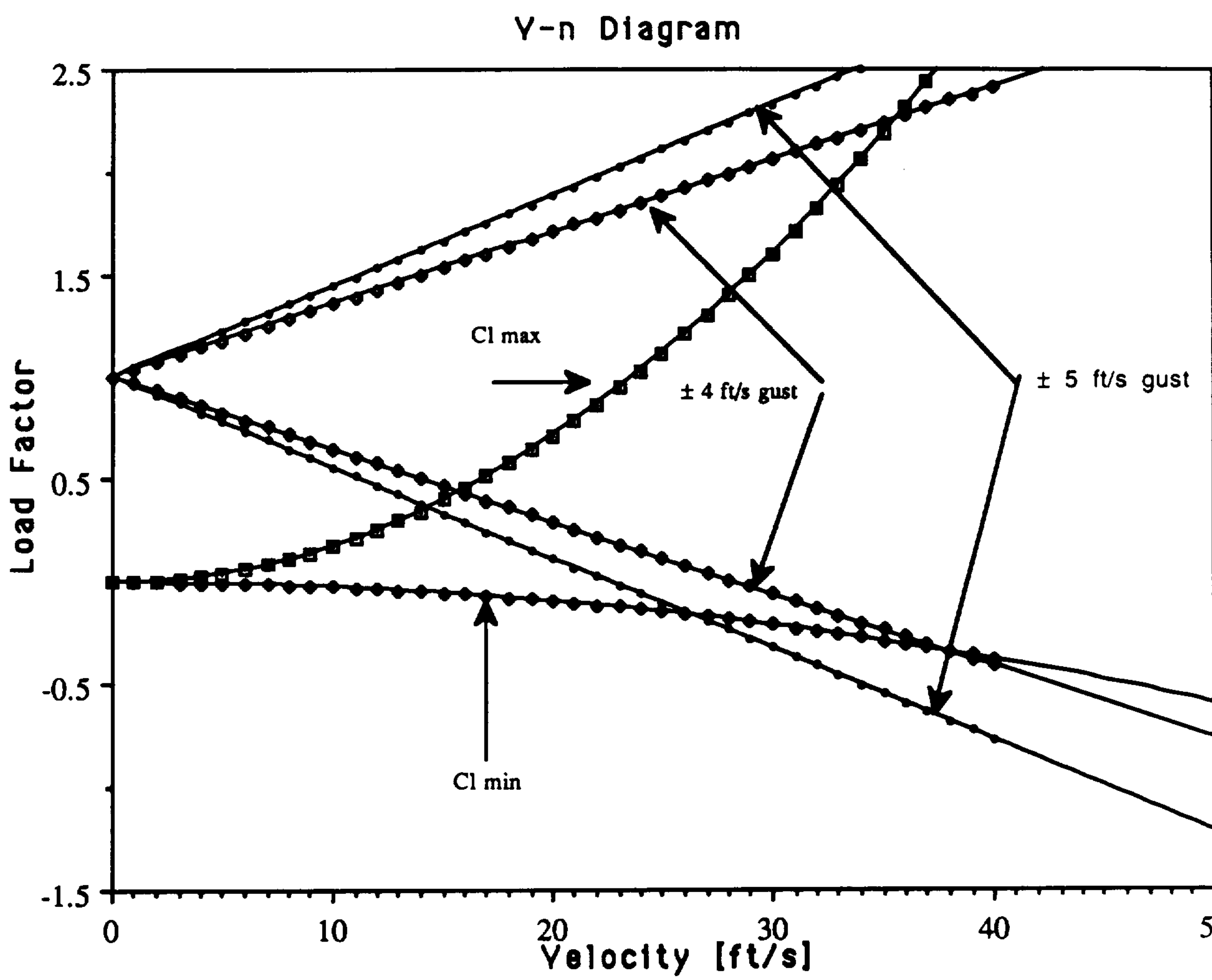


Figure 9.1

In constructing the V-n diagram the following dynamic and structural information

was used:

1). Clmax = .82 & Clmin = -.1
2). Clα = .065/degree
3). Maximum velocity Vd is 35 ft/s (i.e. Mach 1)
4). Positive limit load factor is 2.5
5). Negative limit load factor is -1.5
6). Gusts do exist

A few of these items warrant simple explanations. Item one presents the Clmax and Clmin for the entire aircraft, not just the airfoil. While the *Valkyrie* can travel at speeds up to 70 ft/s, item three represents the maximum allowable flight speed (Mach 1) imposed the aircraft. The maximum load factors presented in items four and five represent design goals imposed upon the aircraft. The item that requires the most explanation is the last one. Even indoors small gusts, natural or forced air circulation in Loftus, can still occur and must, therefore, be taken into consideration. The V-n diagram for the *Valkyrie* was constructed with two sets of gust lines. The more shallow slope corresponds to a gust of ± 4 ft/s, while the steeper slope corresponds to a gust of ± 5 ft/s. The combination of these two lines illustrate the philosophy used to design the Valkyrie structure. Both gust lines indicate that the *Valkyrie* is capable of withstanding ± 4 and 5 ft/s gusts without breaching the maximum load limit while traveling at Mach 1 and cruise, respectively. The other significant safety feature that Figure 9.1 demonstrates is that for any velocity under Mach 1 the aircraft will stall before reaching its maximum load factor.

The concise nature of the V-n diagram makes it an excellent tool to present the in-flight loading environment. However, there are two flight regimes that the V-n diagram cannot present, landing and take-off. Using the definition of the load factor in the vertical plane and assuming appropriate accelerations for each mode of flight, the take-off and landing load factors were calculated to be 1.03 and 2.03, respectively. In the take-off analysis it was assumed that the *Valkyrie* produced

enough lift to generate an acceleration of 1 ft/s^2 upward; while the landing load factor was calculated assuming a worst case situation in which the wing would actually generate a negative lift and the resulting acceleration would be 33 ft/s^2 downward. The other major weakness of the V-n diagram is its inability to present the load distribution on the aircraft. Even with this weakness in the V-n diagram, it would still be sufficient to end the loading discussion here for a conventional aircraft; however, due to the unique nature of the *Valkyrie,* a discussion of the loading environment would not be complete if the unique features of flying wing loading were not discussed. The absence of a fuselage and a horizontal stabilizer have generated several important loading ramifications:

1). All payload must be carried in the wing itself
2). No fuselage to generate forces and moments
3). Fewer items to design and construct
4). Control surfaces and vertical stabilizers must be attached to the wing itself

These four points are not trivial! The first point is significant in that the bending moment at the root chord is actually smaller due to our ability to distribute weight along the span as opposed to concentrating it in a central fuselage. Furthermore, it is important to note that the concept of carrying payload in the wings is not impractical or unrealistic, for even in modern commercial airliners the fuel is stored in the wings. The second point allowed the design of a lighter structure by eliminating the heavy and complicated carry-through and fastening device required in aircraft that do have fuselages. The third point does a good job in speaking for itself. Any time something can be eliminated from the design, more time can be spent designing the other portions of the aircraft. These first three points have all had positive impacts on the evolution of the *Valkyrie's* structure making it lighter and easier to build. The implications associated with the fourth point, however, have generated problem points within the structure; first by

requiring strong attachment locations for the flaps and stabilizers and second by generating unusual loading conditions. By attaching both an elevator and aileron to each half of the wing there exists the very distinct possibility and probability of generating a very large twisting moment about the juncture between these flaps and the main portion of the wing. Intuitively, the worst case situation occurs when the elevator and ailerons are deflected in opposite directions. At the split between these two flaps, differential deflection results in a non-continuous shift in the load distribution of the aircraft, thus generating the aforementioned twisting moment. Since the majority of our flight validation is in an accelerated turning mode (i.e. ailerons are being used heavily), this type of opposite deflection can and will occur quite frequently. The net effect of these problems is the necessity to strengthen certain portions of the wing, which in turn has the effect of adding extra weight and complication to our structure.

9.2 Structure Design Procedure

The procedure used in designing the structure of the wing had several discrete steps to it. The first and probably most trivial decision to make was what type of structure was going to be employed (monocoque, semi-monocoque, or solid core). This decision was trivial only in the fact that there was only one realistic alternative. Although a solid core wing structure negated the need for any type of design work, it clearly was not a possible alternative due to the need to carry the payload in the wing itself. On the other end of the spectrum; the completely monocoque structure offered the greatest internal volume for payload, but was also not a viable option due to the very complicate nature of its construction. Furthermore, a monocoque structure would necessitate the use of various shape memory materials, which would put the structure out of the targeted weight range. Therefore, the structure was restricted to a semi-monocoque structure. In addition

to being the only possible alternative, the semi-monocoque structure also offered its own positive benefits:

1). Relatively light weight
2). "Easy" structure to build
3). Could retain true airfoil shape
4). Plenty of payload volume
5). Ease in attaching the Vertical stabilizers and flaps

Having selected the type of structure employed in the design, attention was focussed on designing the various components of this structure. This process encompassed the remaining steps in the structural design procedure.

In attempting to select the various components that were part of this structure, the design goals for this structure were first established. By accomplishing this first, an objective set of criterion against which the different structural candidates could be evaluated was established. The design goals governed the weight (to be kept under 1.125 lbs or 1.8 oz/ft^2), material selection (use simple and obtainable materials), and construction considerations (make it easy to construct). In addition to these goals, there was of course the obvious goal which requires that the structure does not fail under "normal" loading conditions. As a starting point for component selection and integration, the structural diagrams of other remotely piloted vehicles (obtained from both model airplane kits as well as Mr. Joe Mergen) that have already been validated through flight testing were studied. The goal of performing this study was to determine which structural elements and techniques were common to most, if not all, of these designs. In these designs the following similarities were observed:

1). Extra ribs at leading edge
2). Even spacing of the main ribs (@ 3 to 5 inches)
3). Main load bearing spar(s) in middle of wing

The first feature does not accomplish a structural purpose, and serves more as an aerodynamic device. By placing extra ribs at the leading edge of the wing the

shape of the wing will be more carefully controlled. The second feature has no hidden or mystical purpose to it, but is more or less just a matter of convenience. Finally, the third feature is a function of practicality. The main spar(s) must be large enough to carry and withstand the loading applied to it, and in the center of the wing there is more room for this kind of a structural element. By electing to use these three successful features of other aircraft, it was possible to obtain a mental picture of the pieces to the structure. The final step in the design procedure was an exercise in putting the pieces of this puzzle in their proper place and filling in the blanks left behind. This process followed its own logical progression:

1). Determine rib spacing
2). Double up ribs where necessary
3). Determine spar placement
4). Material selection
5). Select component thickness
4). Evaluate structure against design goals

When all these steps were completed the finalized structure of the Valkyrie (see Figure 9.2) was obtained.

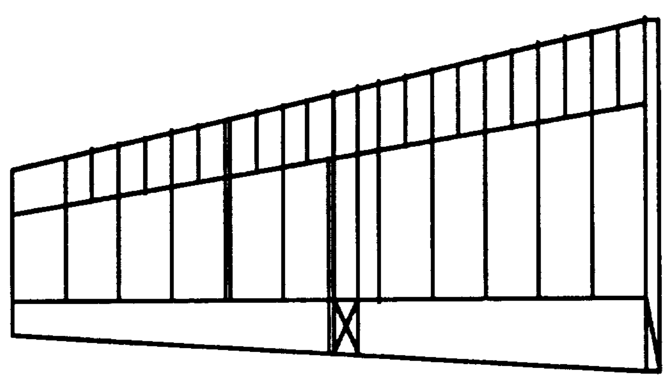


Figure 9.2

As the list above indicates, the first thing to be accomplished was the determination of rib spacing. For the *Valkyrie*, the rib spacing in the structure is really nothing more than a function of passenger spacing. After much

consideration, the decision was made to allow approximately 0.5 inches of spacing between passengers. This spacing combined with passenger size (i.e. 1.5 inch sphere) and the desire to seat two passengers between ribs dictated that the minimum rib spacing be 3.5 inches. On the practical side, if a rib spacing of greater than 3.5 inches was selected potential payload volume would be reduced by excess waste. Next, the number of ribs in the in the frontal section of the wing were doubled for the aerodynamic reasons previously mentioned. Furthermore, double ribs were placed at 22 and 29 inches from the center. The first double rib is designed to give extra support to the vertical stabilizer (which also doubles as a landing gear strut), while the second is present to accommodate the split in the wing structure required by the request for proposal. When all was aid and done, the above design called for 28 ribs per half span. The next step was to determine the spar placement. After some consideration, the decision was made to use two main spars in the aircraft located at 25% and 80% of the chord, for some rather simple reasons. The 25% chord spar was placed in its location for two reasons. First, the center of pressure for any airfoil is very close to the quarter chord point, and this spar location allows us to place the structural support close to the theoretical point of load application. Second, a spar at 25% chord provides a good anchor for the extra ribs in the frontal portion of the wing. The 80% chord spar location was dictated by stability and control considerations. To stabilize the *Valkyrie* it was determined that 20% chord flaps (elevator and aileron) running the entire length of the aircraft were needed. Locating a spar at the 80% chord is advantageous; since it is already necessary to break the structure at this location, and it also serves as a convenient way of connecting the flaps to the main wing. In addition to these main spars, the design also calls for small spacers between each airfoil at the leading edge. These spacers are not intended to carry much load, but are there to help maintain the proper airfoil shape across the front of the wing. The information discussed to this point allows

the presentation of the two dimensional structural representation found in Figure 9.2. The next step was material selection and thickness. Please recall that one of the structural design goals was to keep the number of materials down. To this end, two materials have been selected to be utilized in the main structure of the aircraft; one soft wood, balsa, and one hard wood, spruce. Every rib in the structure will be made of balsa wood. The main ribs that run the entire length of the airfoil will be 1/8 (.125) inches thick, while the redundant and extra leading edge ribs will be 3/32 (.09375) inches thick. The extra 1/32 (.03125) inches was shaved off these extra ribs, because this has the potential to reduce the structural weight by over .1 pounds. On the other hand, the ribs cannot be too thin, for one consideration that cannot be overlooked is that the aircraft is going to be manhandled and subjected to possible breakage if certain elements are too thin. Since the main spars will carry more load and subsequently need to be stronger than the ribs, the spars will be constructed of both spruce and balsa of varying thickness. For ease in construction, the 80% chord spar will be made of entirely balsa 1/4 (.25) inches thick, to which the ribs will be flat mounted. The 25% chord spar, is unfortunately a little more complicated. The overwhelming reason for the extra complication is that it was undesirable to split every rib at the 25% chord position, for this would significantly weaken the overall structure of the aircraft. The 25% chord spar was thus constructed in the following manner. A 1/4 (.25) inch high strip of spruce was run along both the top and bottom of the wing at the 25% point, and connecting both these pieces is a 1/16 inch thick sheet of balsa. This spar structure has several advantages. First, it effectively produces a thicker spar which will in turn distribute the load more evenly. Second, this structure increases the area moment of inertia of the spar, which will in turn reduce the stress due to bending in the structure. Please see Figure 9.3 for a cross sectional view of the 25% chord spar.

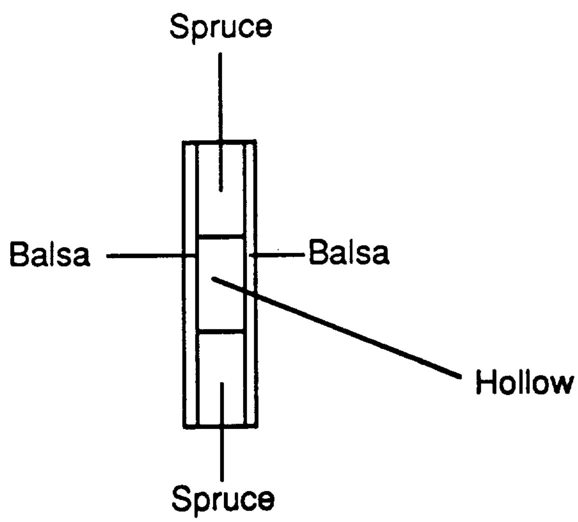


Figure 9.3

The elements presented above make up the basic structural framework of the aircraft, and will be complimented with both the necessary bulkheads for avionics installation as well as a thin heat shrink film such as mylar for the skin. The information presented above is a candidate design, which needs to be evaluated against the self imposed design criteria. Presently, calculations put the weight of the *Valkyrie's* structure around 1 pound, which allows a little room for error. Secondly, the relatively few number of materials used should simplify construction as much as possible. The weight and ease of construction mean nothing, however, if the structure will not withstand normal loading conditions. To this extent the structure was modeled and processed by a finite element analysis program developed at the University of Notre Dame entitled SWIFTOS. This program generates the stresses present in the structural members. While the data generated by this program is too extensive to present here, the numbers generated by the program indicate that the structure will not fail. Being individuals that do not blindly trust computer programs some simple back of the envelope calculations were performed to verify these results. As a very conservative estimate (considering lift only) we calculated a

root bending moment of 563.75 lb-in. Using the simplest of models the structure can withstand a bending moment of over 700 lb-in. The *Valkyrie* structure is well within this limit. Having developed a design that meets and exceeds all of the design criteria, the above stated concept was accepted as the finalized structural design of the *Valkyrie*.

9.3 Payload

In electing to go with a flying wing design, a few of the conventional problems associated with aircraft design were eliminated. In doing so, however, a few non-conventional questions were generated that must be answered. Because this aircraft must carry its payload (i.e. passengers) in the wing itself, one of the most important questions that must be answered is internal configuration (passenger placement). With a design goal of 100 passengers this proved to be no trivial task! The first question asked was whether or not it was possible to carry 100 passengers in the wing? The answer was a resounding yes! Not only is it possible to carry all 100 passengers, but they can be carried in comfort as well. A FORTRAN code generated a conservative estimate of how many passengers can be seated in a chord-wise fashion at a given location along the span. A complete listing of the program can be found in the Appendix. As input to the program passenger spacing in all three dimensions was required. The program then modeled the passengers as rounded oblong objects of the following dimensions; length (span-wise) 1.8125 inches, height 1.7 inches, and width (chord-wise) 1.6 inches. The spacings were accounted for so that the program could account for both structural elements as well as passenger spacing. Provided with the geometry of the aircraft, this program generated a seating chart for the aircraft. This seating chart is presented in Figure 9.4.

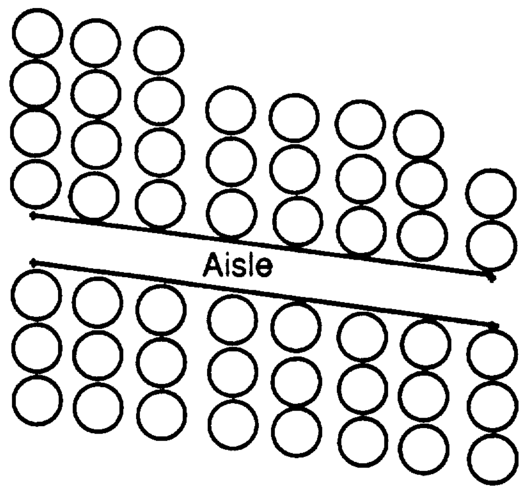


Figure 9.4

Just as important as passenger placement is passenger access (i.e. how they get in and out of the aircraft). In Figure 9.4, note that there is an aisle down the center of the passenger portion of the aircraft. Passenger access will be through an underneath hatch with stairs leading up to this aisle. This type of passenger access will allow our aircraft to be serviced by existing jetways at the airports. The passengers would simply walk down a flight of stairs from the terminal, across the tarmac to the aircraft, and up the stairs into the passenger compartment. Emergency evacuation will be by a series of emergency hatches placed on the top and bottom of the wing. An important consideration of the structures and payload is the mass moment of inertia about the center-line of the aircraft. The breakdown is presented in Table 9.1

Table 9.1

Component		Ix [slug-in^2]
ribs		3.766
spars		9.2
people		0.716
avionics		0
vertical stabilizers		3.65
total		17.36

As a last note of explanation, the avionics do not contribute significantly to the moment of inertia, because they are concentrated at the center of the aircraft.

9.4 Landing Gear

Due to the unique nature of the landing gear on the *Valkyrie* the discussion of this component has been delayed until now. The *Valkyrie* utilizes a hybrid of a standard tail dragger and tricycle landing gear. Like the tail dragger landing gear, the *Valkyrie* sits on the ground on its rear wheels. Unlike the tail dragger, however, the *Valkyrie* has two wheels in the rear and one wheel in the front. This design utilizes the large vertical stabilizers in the rear of the aircraft as landing gear struts. This has the effect of reducing drag on the aircraft. The drawback with this hybrid landing gear design is its inability to rotate the aircraft at take-off. This problem requires that the nose gear be long enough so that the aircraft is mounted at the take-off angle of attack. The rear wheels of this landing gear have been designed with adjustable mounts so that the take-off angle of attack can be precisely set at the required value.

9.5 Center of Gravity

For a flying wing aircraft the location of the center of gravity is a very important parameter. Stability and control dictates that the center of gravity must reside in a very narrow region. This necessity, coupled with a lack of information on the densities of the various materials, make an accurate prediction of the center of gravity quite difficult. Thus, it was concluded that the full discussion of the center of gravity of the aircraft be suspended until the technology demonstrator section of this report (see section 13.6).

Having exhaustively examined both the aerodynamics and the structural considerations of the Valkyrie, this discussion proceeds to synthesizes these analytical domains in the a brilliant stability and control discussion.

Stability and Control

Section 10. Stability and Control of the Valkyrie

The static stability and control of a flying wing is arguably the most critical aspect of the entire design process. LinAir 1.4 was used extensively throughout the control analysis. LinAir uses a discrete vortex Weissenger method which is particularly useful in the absence of experimental verification. This method allows for the computation of the aerodynamic characteristics of multi-element, nonplanar lifting surfaces.

Our aircraft is easily modelled on LinAir. Our aircraft utilizes the $2R_2$-12 airfoil section, therefore, C_{Lo} is nearly zero and Cm_{ac} is nearly zero over all angles of attack of interest as shown in the section on aerodynamics. Thus, by simply inputting the location of the center of gravity and the geometry of wing, elevator, and ailerons (as three separate elements), aerodynamic coefficients and derivatives can easily be determined for the entire aircraft.

A computer program was created which facilitates quick calculation of all necessary data for LinAir 1.4. The program subsequently creates a file which can then be read directly by LinAir. This program was used extensively in the sizing of the elevator and ailerons and its listing can be found in the appendix.

The vertical stabilizer and rudder were modelled separately as a general lifting surface in order to determine the appropriate aerodynamic coefficients and derivatives. The effectiveness of the elevator, rudder, and ailerons were able to be modeled with a fair amount of accuracy. The methodology used has been shown to correlate well with theory. (See reference [1])

10.1 Longitudinal Static Stability and Control

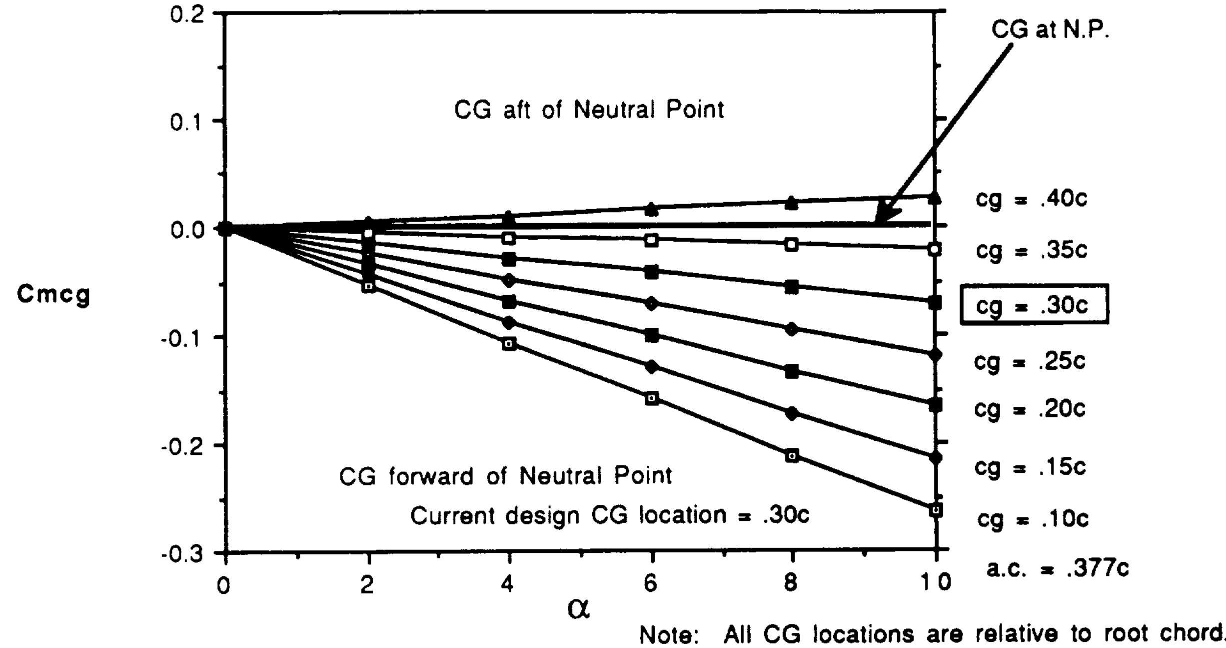
Two conditions must be satisfied in order to achieve longitudinal static stability. First, the aircraft pitching moment curve must have a negative slope, i.e. $Cm_\alpha < 0$. Also, the curve must have a positive intercept, i.e. $Cm_0 > 0$. Since this is a flying wing, only the wing contributes to the static stability. Both conditions are determined by the position of the center of gravity. The intercept is also a function of the elevator size.

The neutral point is the aerodynamic center of the wing and is therefore fixed by the geometry of the wing. By modeling the wing in LinAir, the neutral point can be calculated by the following equation:

$$\frac{N.P.}{c} = c\,\frac{\delta C_m}{\delta C_L} + \frac{C.G.}{c} \qquad (1)$$

With the planform geometry fixed, the mean aerodynamic center (neutral point) is fixed at 50% mean chord (37% root chord). By varying the position of the center of gravity, the influence of the center of gravity position can be shown as in Figure 10.1. The location of the static margin can also be visually verified on Figure 10.1.

Figure 10.1:
Influence of Center of Gravity Position on the Longitudinal Stability



The larger the static margin, (i.e. the further forward the center of gravity) the greater the pitch stability of the aircraft. However, there emerges practical limitations as shown in Figure 10.2. The larger the static margin is, the greater the elevator deflections required to trim the airplane. Consequently, greater angle of attacks are needed to offset the decrease in lift. Very quickly we can proceed to stall. Therefore, the permissible center of gravity locations are between 23% and 37% root chord (31% and 50% mean chord). A center of gravity at 30% root chord (41% mean chord) was selected. This position lies in the center of the acceptable range. Our static margin of 9% mean chord offers sufficient static stability while allowing us to retain the ability to trim the aircraft with moderate angles of attacks and corresponding elevator deflections at all flight phases. By selecting the center of the acceptable range, we allow for slight shifts of the center of gravity location due to

asymmetric passenger loadings, which could be on the order of +/- 3% mean chord. The preceding analysis indicates, as illustrated in figure 8.1, that $C_{m\alpha}$ ranges between -0.573 and -0.227 for the forward and aft cg. locations, respectively.

Figure 10.2:

Angle of Attack and Flap Delection Angle to Trim for Various Center of Gravity Locations @ Takeoff

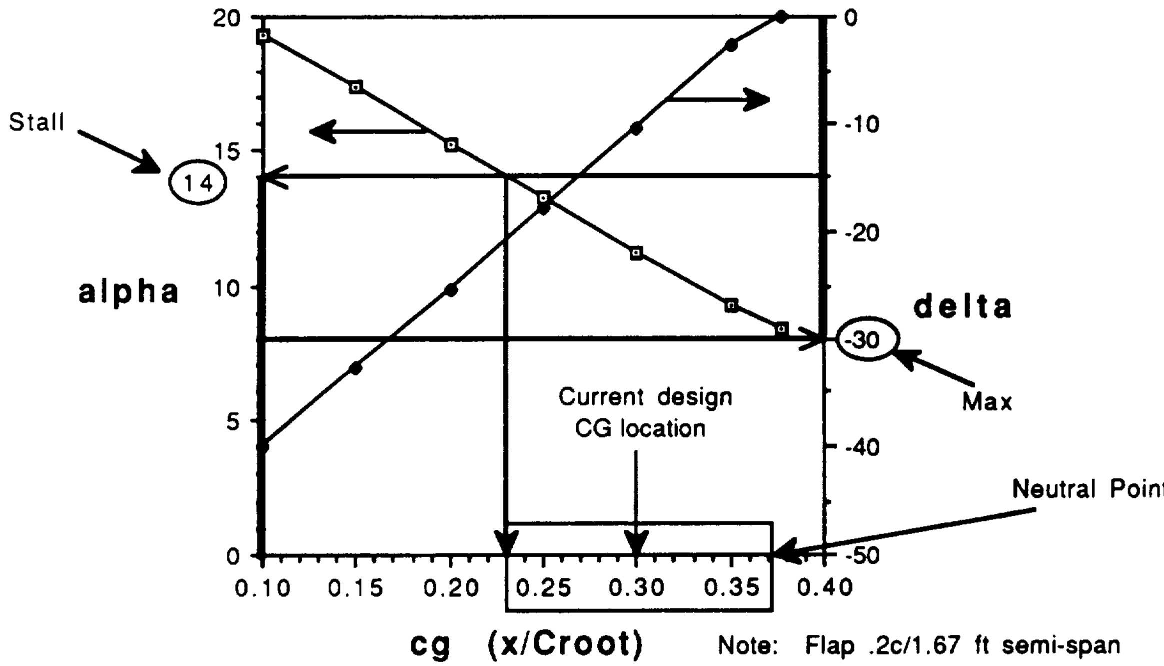


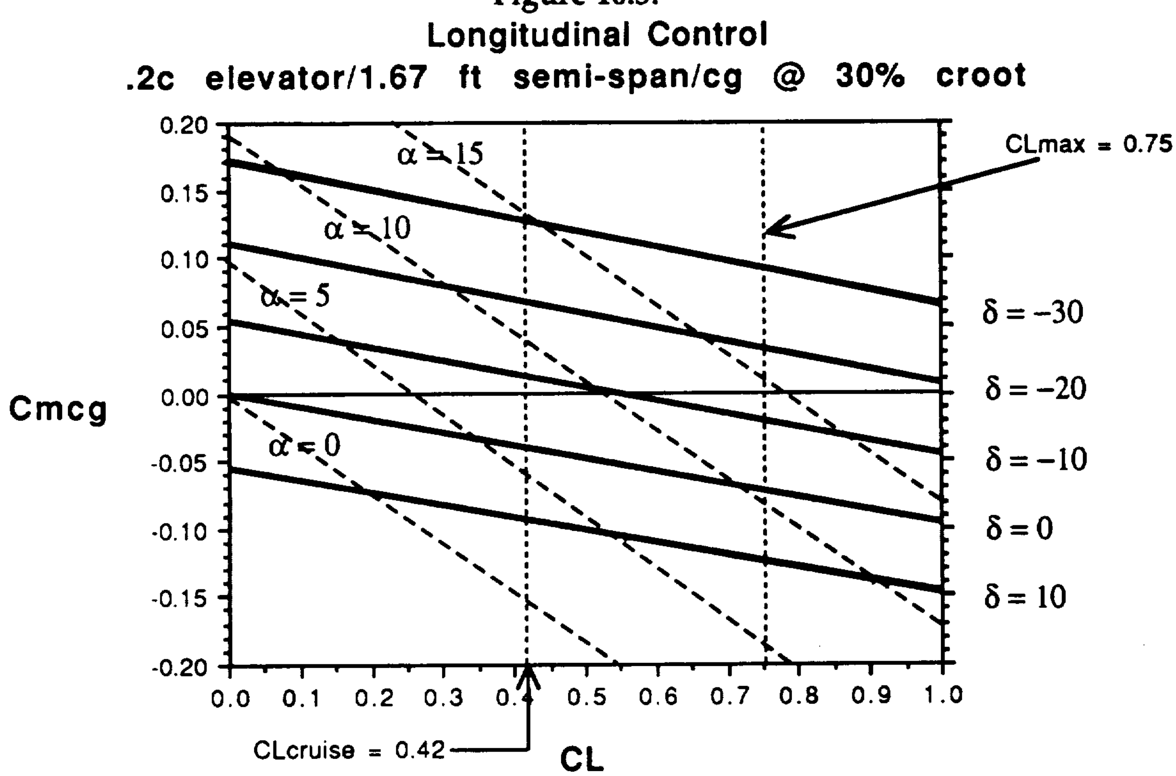
Figure 10.3 is a plot of the longitudinal characteristics of the Valkyrie. The plot gives the angle of attack and elevator deflection necessary to trim at any C_L. Table 10.1, on the following page lists three critical flight stages and the C_L, the angle of attack, and the elevator deflection required at each stage. For discussion of drag generated due to flap deflection see *Aerodynamic* s, section 8.

Table 10.1:

Flight Stage	C_L	α (degrees)	δ_e (degrees)
cruise	0.42	8	-8
take-off	0.58	11	-11
$C_{L\ max\ trim}$	0.75	14	-14

From Figure 10.3 below, it can be determined that Cm_α = -0.4. This offers acceptable pitch stability, but we would suggest a stability augmentation system on the production model to ensure greater safety and comfort to the passengers.

Figure 10.3:



10.2 Lateral Static Stability and Control

The size of the vertical stabilizer required is determined through simple manipulation of the volume ratio equation:

$$V_v = \frac{l_v S_v}{cS} \quad (2)$$

A database search of similar aircraft vertical tail volume ratios revealed a typical value of 0.027. With a moment arm of 1 foot, a total of 2 ft^2 provides a volume ratio of 0.029. Because of the enormous stabilizer area required, the area will be equally divided between three vertical stabilizers.

Assuming there is no sidewash effect, $C_{n\beta}$ can be calculated from the following equation:

$$C_{n\beta} = V_v \eta_v C_{L\alpha v} \quad (3)$$

Assuming η_v is to equal approximately 1 and determining C_{Lav} to be 2.87 rad^{-1}, $C_{n\beta}$= 0.082 rad^{-1}.

At takeoff, with the wing at a 10 degree angle of attack, there is a possibility that a significant percentage of the vertical stabilizers may be shrouded by the wing's wake. That portion shrouded by the wake would be ineffective in providing yaw stability at takeoff. It is for this reason that thirty-five percent of the total stabilizer area is mounted beneath the wing.

Since ailerons are incorporated into the *Valkyrie's* design, and there are no cross-wind landing requirements in Aeroworld, a rudder need not function as a primary control device. However, in order to ensure maximum safety, Group ζ, the designers of the *Valkyrie,* have imposed this requirement in order to deliver an airplane that meets or exceeds all safety requirements.

The rudder is sized in order to maintain alignment with the runway at landing under the influence of a 10 ft/s cross-wind. A cross-wind of this magnitude constitutes an effective angle of attack of 20 degrees on the vertical stabilizers at landing. The total rudder area necessary was determined by modeling this aerodynamic surface on LinAir 1.4. The vertical stabilizer was modelled as a wing and subjected to a -20° angle of attack. The rudder deflection was then varied until

the aerodynamic lift coefficient was neutralized. The drag component contribution to the moment was considered small, and thus neglected during this analysis.

The rudder size necessary to overcome this critical condition is 38% or 0.75 ft^2. A corresponding rudder deflection of approximately -25° is required to maintain the aircraft heading at this critical condition. The total rudder deflection allowed is ± 30 degrees.

The center rudder is linked to a servo. The lateral rudders are attached to the center rudder with a rod. Since this rod will lie directly aft of the trailing edge, no great drag increase is anticipated due to this addition. A single small wheel mounted on each lateral rudder provides directional control and stability during taxiing. A third, long strut, wheel is mounted near the leading edge forward of the cg. This type of landing gear configuration, tricycle/tail-dragger allows for reduced drag by eliminating two long landing gear struts and allows the *Valkyrie* to be fixed at the takeoff angle of attack.

10.3 Rolling Static Stability and Control

Roll stability is achieved by 13° of wing sweep and a 2° dihedral. It is necessary to have enough control power to complete a turn with a 60 ft radius. The roll control of the *Valkyrie* was analyzed for a 50 ft banked turn (for added safety) by the simplified equation of motion:

$$I_x \Phi = L_{\delta a} \delta_a \quad (4)$$

The moment of inertia for the aircraft about the x-axis, calculated in **Section 9: Structures and Payload**, is approximately 0.1206 slug*ft^2. The rolling angular acceleration, Φ, required was determined by estimating the time allowable to achieve the necessary bank angle, θ.

$$\Phi = \frac{2\theta}{t^2} \quad (5)$$

The *Valkyrie* has been constrained to respond to a moderate aileron deflection by attaining the necessary bank angle of 32.3° in 2 seconds. This requires and angular acceleration of 16.15 rad/s.

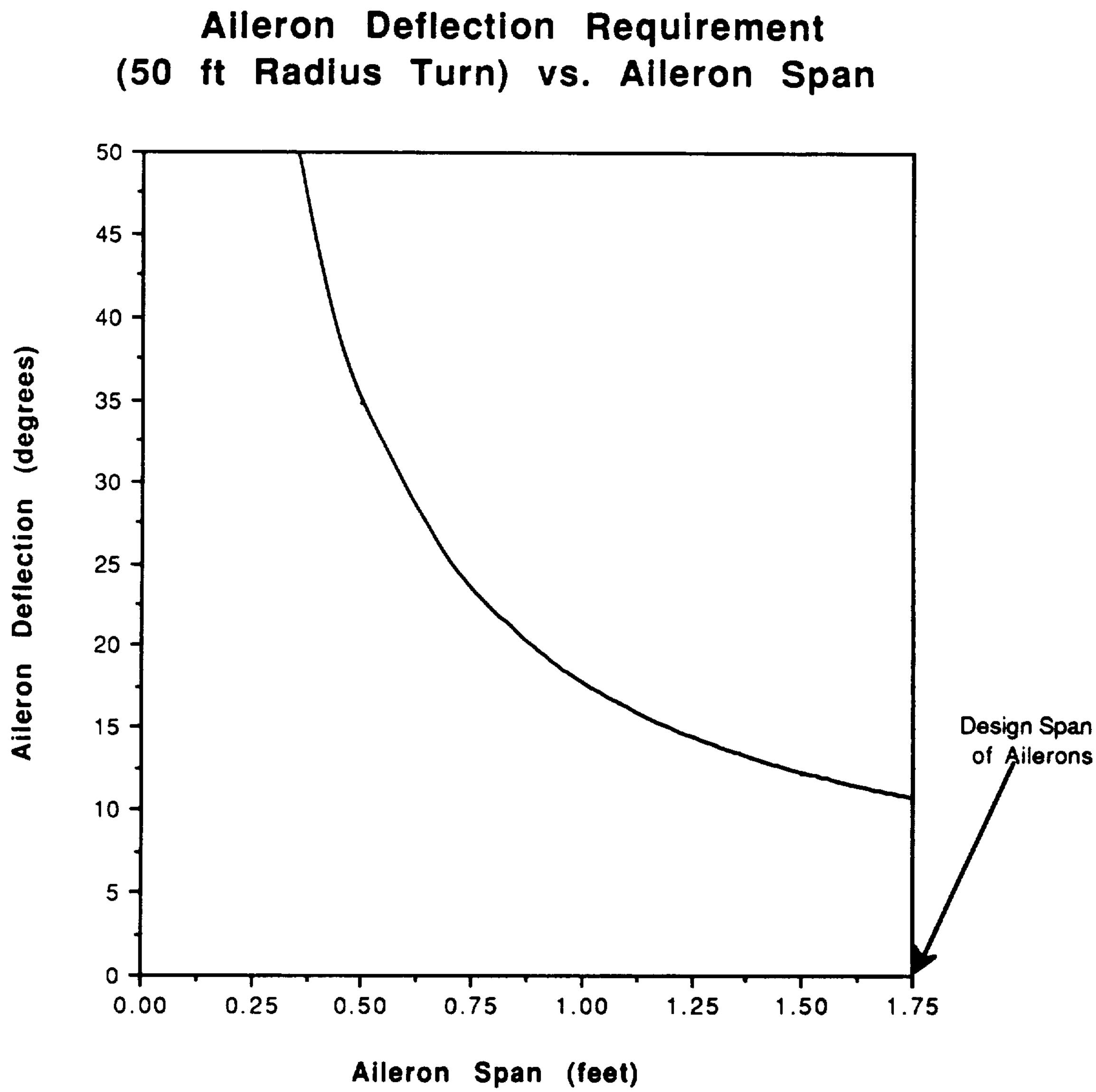
The roll control power coefficient, $Cl_{\delta a}$, can be calculated by the following equation:

$$Cl_{\delta a} = \frac{2C_{L\alpha\omega}\tau}{Sb}\int_{y_1}^{3.5} cy\,dy \qquad (6)$$

$$L_{\delta a} = Cl_{\delta a}QSb \qquad (7)$$

where the equation of the chord (in feet) is $c(y) = -0.2857y + 1.917$ and Q, at cruise, equals 1.217 lb/ft^2. The length of the aileron was then varied and the corresponding aileron deflection was determined. The results can be found in Figure 10.4.

Figure 10.4



Utilizing all available span requires approximately a 12° aileron deflection. Therefore, the aileron will span from the vertical stabilizer to the wing tip for a total semi-span of 1.75 ft with a total area of 0.817 ft^2. The allowed range of deflection will be +/- 20°.

References:

1. LinAir for the Macintosh, Version 1.4, Desktop Aeronautics, Stanford, CA, 1987-90.

2. Nelson, Robert C., Flight Stability and Automatic Control, McGraw-Hill Book Company, New York, 1989.

Propulsion

Section 11. Propulsion

11.1 Engine - Propeller Selection:

As in any design procedure, selecting a propulsion system seeks to most effectively satisfy all critical phases of the desired mission, while simultaneously striving to optimize certain parameters designated by the overall mission proposal. In this case, the overall mission objective aspires to maximize profit, and from an electric motor propulsion perspective, this implies attempting to minimize the current draw necessary to maintain a cruise condition. And, as a secondary consideration, the electric potential (voltage power setting) necessary to achieve this cruise condition has been investigated in order to determine the minimum number of batteries required by each given engine-propeller combination. Minimizing the number of batteries reduces the overall weight of the propulsion system, and thereby influences the total structural size of the aircraft.

However, besides optimizing in the cruise configuration, the engine-propeller must be capable of effectively completing all phases of the overall mission. After examining the relevant performance requirements for all phases of the mission, takeoff emerged as unquestionably the most critical phase. Takeoff, for a flying wing in particular, requires a complex integration of stability and control, aerodynamic and propulsive considerations in order to achieve success. The flying wing possesses an inherent difficultly in generating the critical nose-up pitching moment necessary for rotation during takeoff. More specifically, the rear flaps must be deflected up, rather then down, so to achieve the required moments. This action, although imperative to the aircraft's stability and control, produces a dramatic loss in lift which can only be overcome by increasing the takeoff velocity. Obviously attaining higher takeoff velocities requires elevating the available excess power.

Figure 11.1 Effect of Variation in Propeller Diameter and Engine Size on Current Draw and Voltage requirement (Cruise)

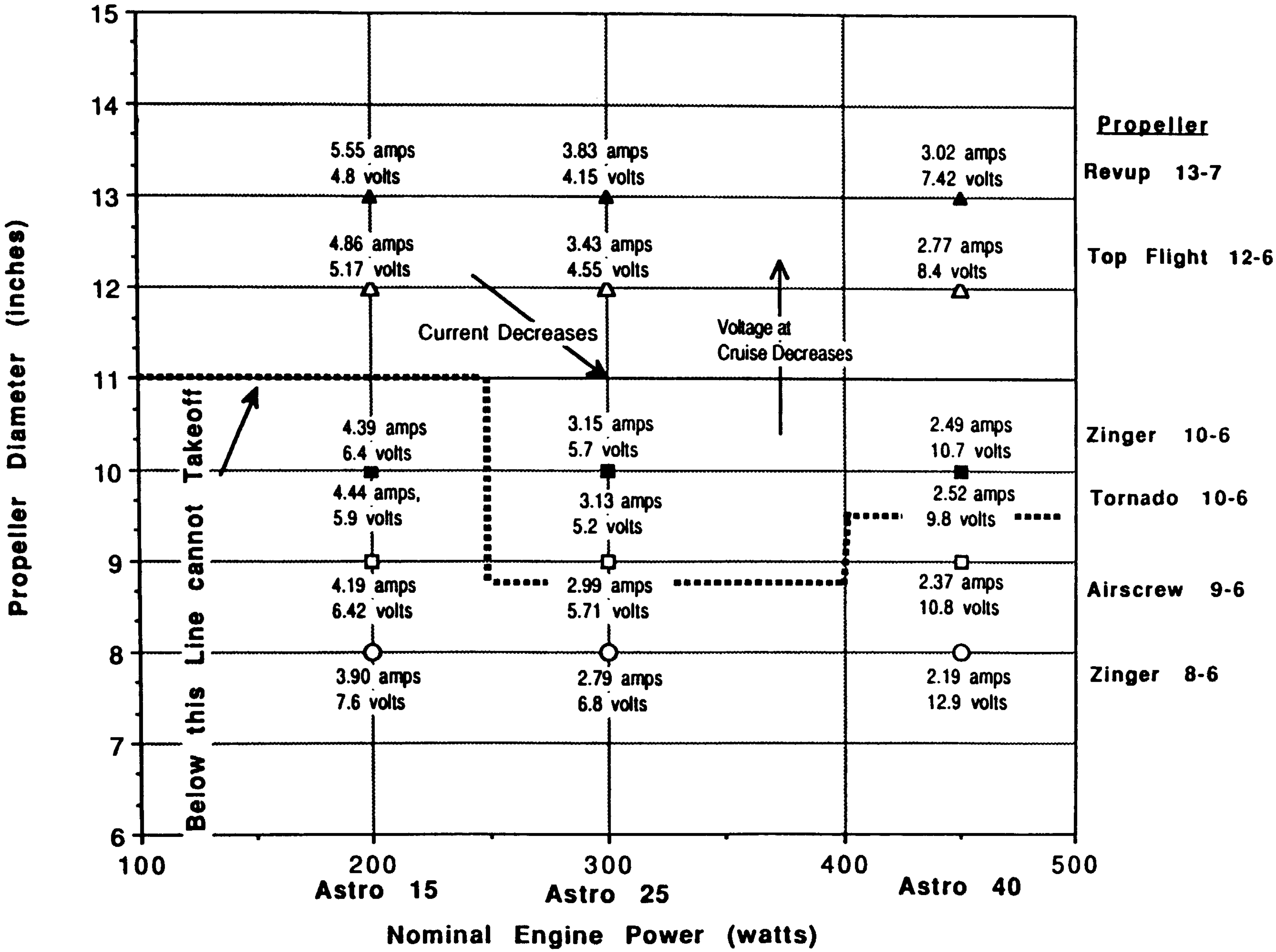


Figure 11.1, shown on the preceding page, illustrates the current and voltage requirements for various motor-propeller combinations. As shown on the plot, the current and voltages necessary to maintain the cruise condition develop distinct trends according to variations in propeller diameter and engine power (or motor size). As the propeller diameter decreases, the current required by the propeller to maintain cruise also decreases. Similarly, as engine size rises, the current required to achieve steady level flight also decreases. These trends alone would lead one to select the largest engine with the smallest propeller, however, takeoff requirements have not yet been imposed. The thick black dotted line isolates those engine-propeller combinations which are incapable of taking off with a Cl_{to} of 0.48 on a 75 ft runway (below the line cannot). These trends, sensitivities and constraints direct the selection to the Astro 25 with the 9 inch Master Airscew propeller or the 10 inch Zinger (or Tornado) propeller, or, the Astro 40 with the 10 inch or possibly the 12 inch propeller. Employing the Astro 40 is immediately eliminated for two reasons. First, regardless of the particular propeller, implementing the Astro 40 necessitates an additional 10 oz of propulsion system weight, and considering the Valkyrie only seeks to carry approximately 9 oz of passengers, this option is quite impractical because it severely diminishes the aircraft's ability to transport passengers and haul cargo. In addition, although the Astro 40 with the 10 inch diameter propeller can takeoff, it requires 71 ft of runway to do so; Four feet of safety margin, considering the uncertainty in such calculations (esp. in μ), leaves the designer, not to mention the passengers, feeling rather insecure.

Based on this analysis the investigation narrows its focus to the Astro 25 engine with either the 10-6 Tornado propeller (the Tornado consistently produces more favorable characteristics than its competitor the Zinger 10-6) or the 9-6 master Airscrew. Final selection decisions emphasized the importance of the critical

Figure 11.2 Variation in Voltage according to Engine Power for various Diameter Props.

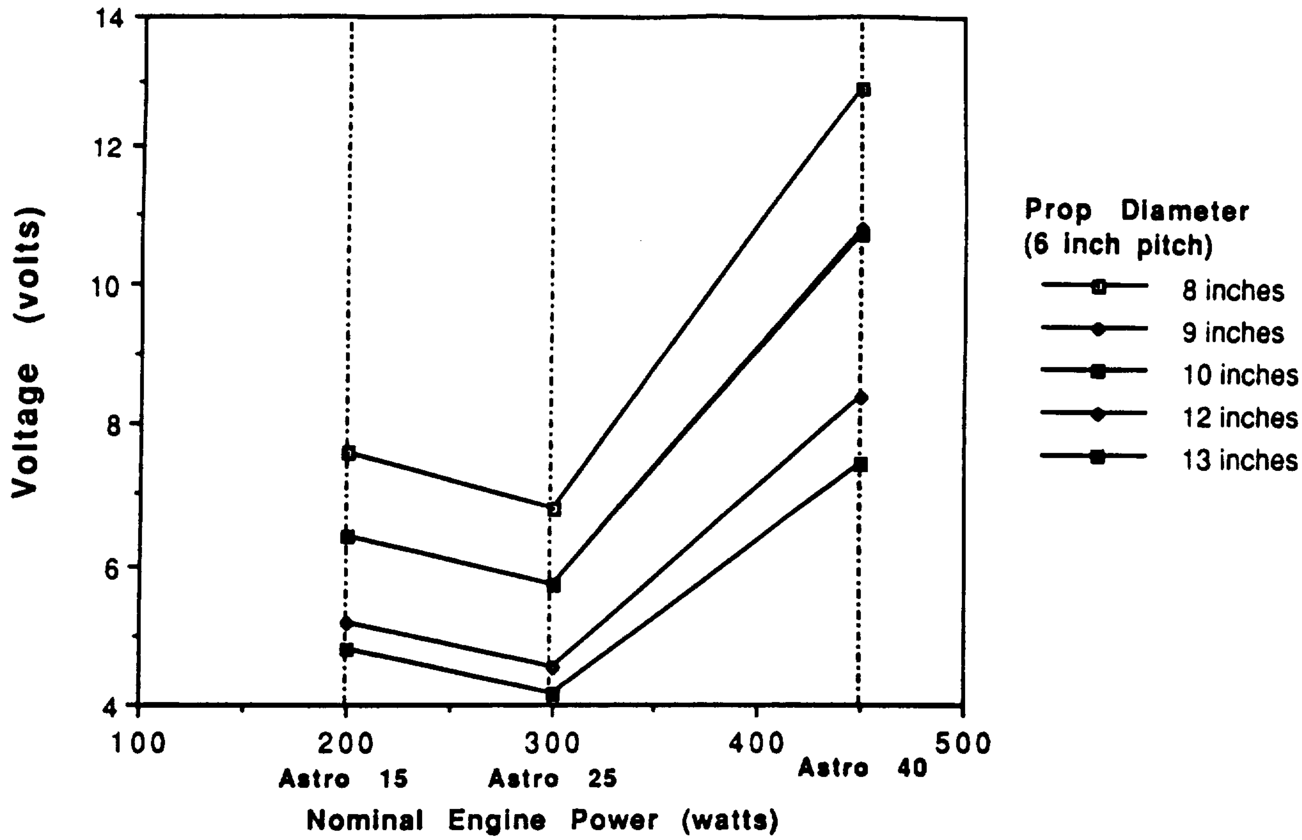
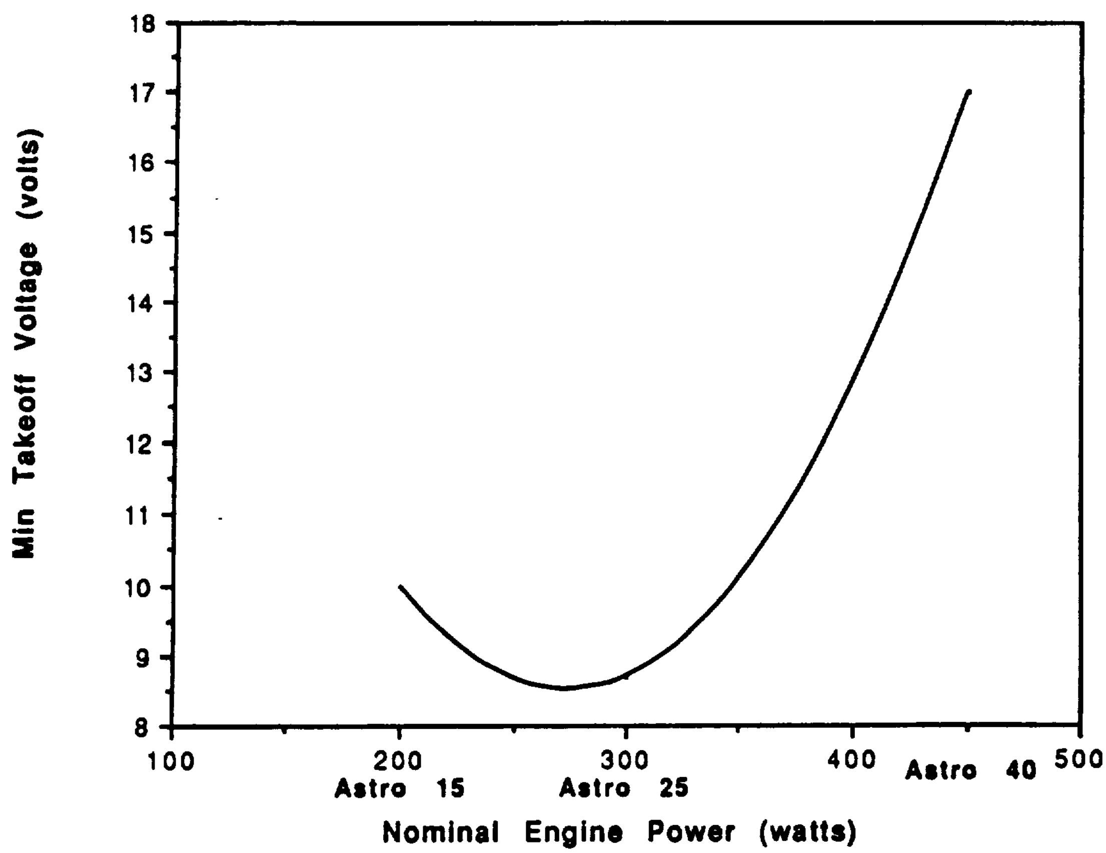


Figure 11.3 Variation in Min required Voltage with Engine Power for various Diameter Props. (takeoff)



takeoff phase; the Tornado 10-6 was ultimately chosen in order to ensure the availability of excess power during this stage.

Notes on Figure 1.

- All geometric and weight parameters (weight was 5.02lbs, for geometric parameters see section 8) are held constant

- Max recommended voltage settings, according to the number of batteries, were employed during the takeoff analysis. 12 batteries were employed for the Astro 15, 14 for the Astro 25, and 18 for the 40.

- Because of minor alterations in later designs the currents and voltages do not exactly mirror our present predictions, however the trends and conditions remain valid. The relative position of the takeoff condition has **not** changed.

The Astro Cobalt 25 has another important characteristic besides its power availability and fuel efficiency that makes this motor the obvious choice for the Valkyrie's propulsion requirements. Figure 11.2 shows the voltage setting necessary to maintain the cruise condition for each of the motor-propeller combinations. As is clearly observable from the plot, for every propeller diameter, the Astro 25 requires the lowest voltage setting to maintain the cruise condition. In a similar fashion, figure 11.3 shows the minimum power setting (voltage) at which a given engine equipped with the Tornado 10-6 is still capable of taking off (in 75ft) Again, of the 3 engines under investigation, the Astro 25 demands the lowest voltage, and thus the fewest number of batteries to achieve takeoff. And, in particular when employing electric motors, fuel cell weight represents an important design consideration; the Astro 25 allows the Valkyrie to reduce the impact of this constraint thereby providing more space for more passengers and cargo, without increasing the total weight.

11.2 Design Presentation

The following section presents a summary of proposed propulsion system for the Valkyrie air transport system.

Propulsion System

1 Astro Cobalt 25 equipped with the Tornado 10-6 Propeller
-2 blades

Power Pack:

12 1.2 volt, 1. amp hour batteries yielding

15.4 volts of power

Cruise Conditions (Velocity=32 ft/s):

Voltage Setting: 6.3 volts

Current Draw: 4.24 amps

Prop RPM: 4670.

Power Available: 21.2 watts

Thrust: 2.18 N

Prop Efficiency: 0.833

Max Range: 13,300 ft

Takeoff (maximum conditions, Voltage=15.4volts)

Velocity Takeoff: 26.4 ft/s

Static Current Draw: 15.1 amps

Max Motor Power: 475. watts

Static Thrust: 3.90 lbs

Battery Drain: 5.70 mahs

Takeoff Distance: 16.8 ft

Static Prop RPM: 10, 500

Figure 11.4 Takeoff Distance Required at Voltage Setting

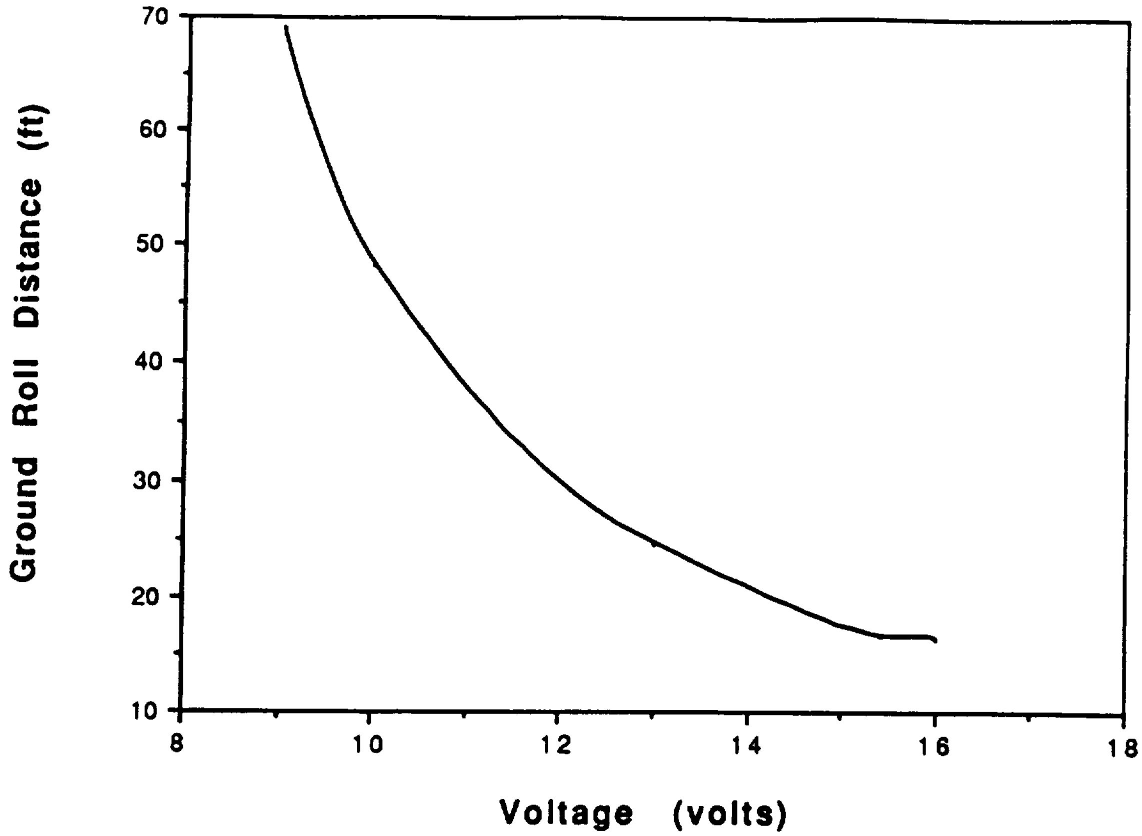
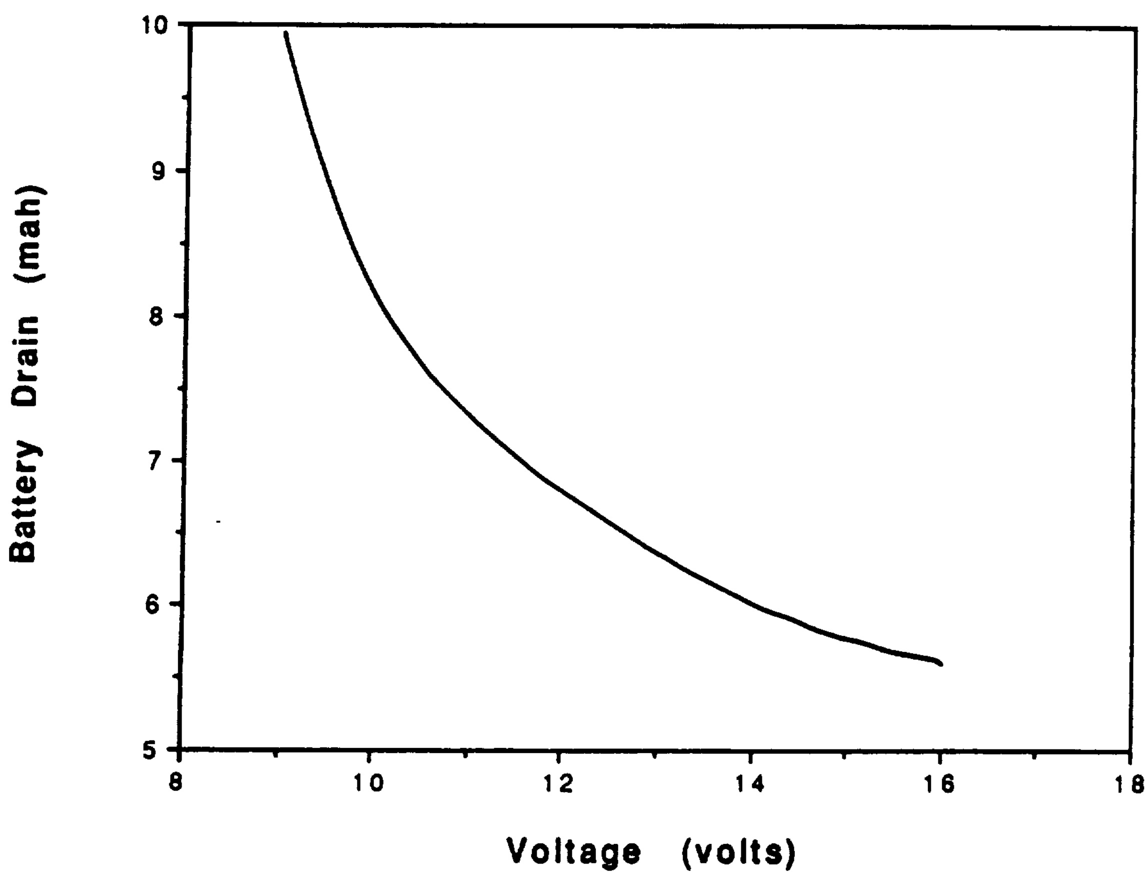


Figure 11.5 Battery Drain according to Voltage Setting



Time: 1.35 seconds

Takeoff analysis suggested that the Valkyrie with this available voltage (12 batteries -15.42 volts) will achieve lift-off at a velocity of 26.4 ft/s with only a 16.8 ft runway. Decreasing the the duration of the takeoff taxi diminishes the battery drain, consequently providing more available energy for the latter phases of the mission.

11.3 Takeoff Analysis:

Figure 11.4 demonstrates the variation in ground roll distance for variation in the voltage power settings. Clearly, as expected, the required takeoff distance drops as the power setting increases. At approximately 15.42 volts (maximum power for 12 batteries -present design) the curve begins to level off. Increasing the voltage power available, by increasing the number of batteries, provides little decline in the ground roll distance. A comparison of figures 11.4 and 11.5 illustrates that battery drain (for takeoff) and ground roll distance respond similarly to changes in the available power. Elevating the maximum voltage requires increasing the number of batteries, however, as is clear from figure 6, even large increases in voltage do not significantly diminish the battery drain. The extra weight for 1.2 more volts of power is 1 oz which is the equivalent of 15 passengers. It would not pay to carry any more batteries.

Figure 11.6 illustrates the variation in static thrust with changes in the power setting. At a voltage of 15.42 volts the Valkyrie achieves a static thrust of 3.9 lbs. The power setting can be as low as 9 volts, with a static thrust of 1.58 lbs, and still manage a takeoff. Voltage settings below 1.05 lbs cannot overcome the static friction restrictions, while, voltages between 1.05 and 1.58 lbs can takeoff, but not in 75 ft.

Figure 11.6 Static Thrust at Voltage Setting (for takeoff)

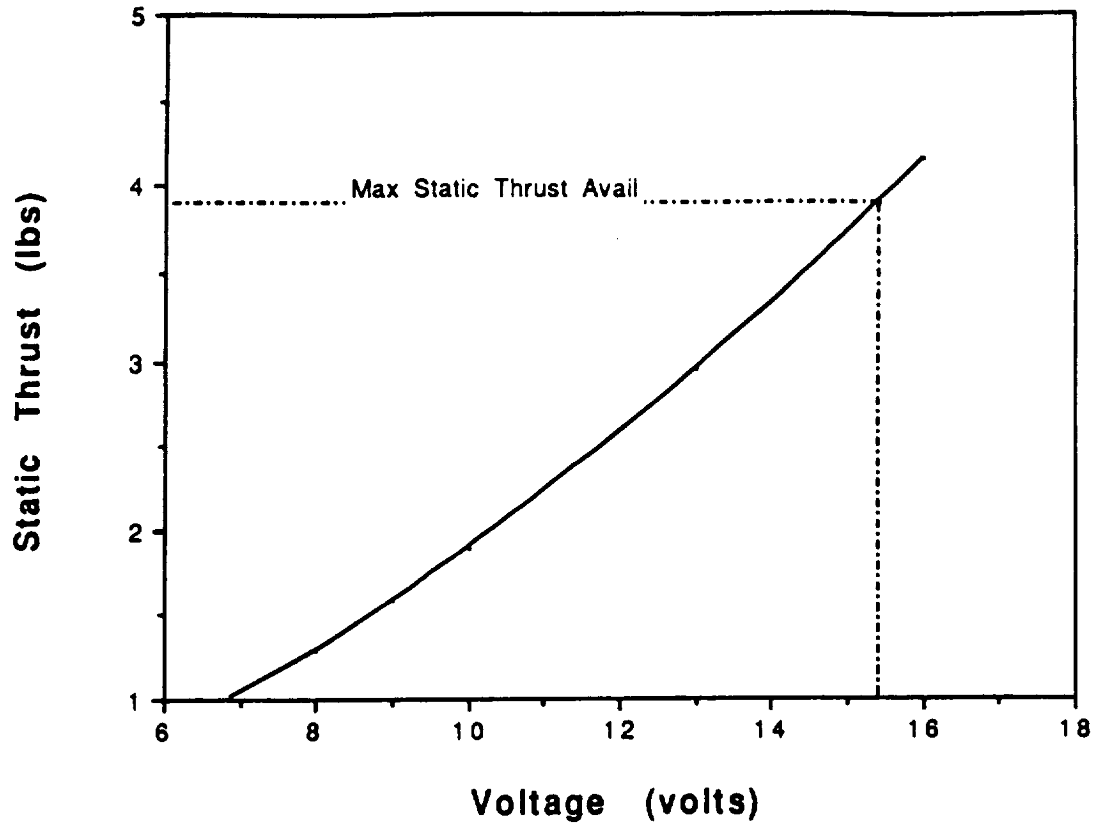
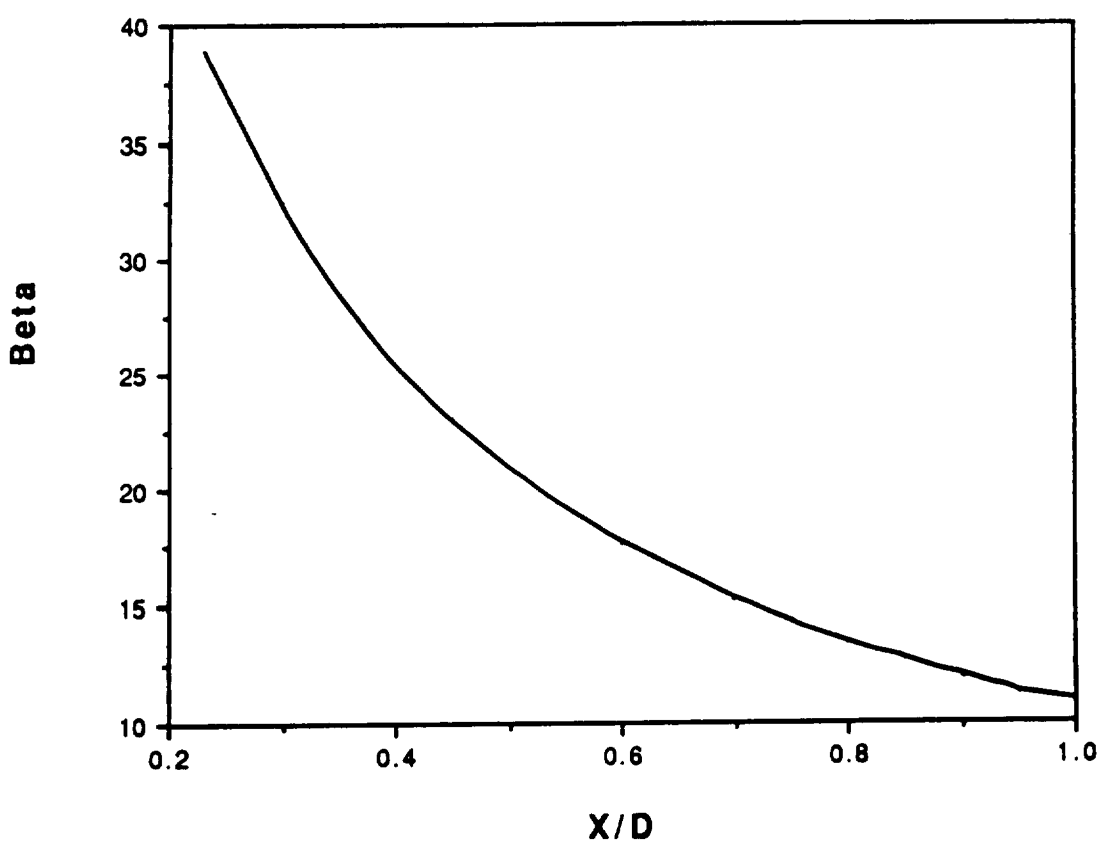


Figure 11.7 Pitch (Beta) vs Prop Span



11.4 Propeller Performance Analysis

Figure 11.7 demonstrates the variation in propeller pitch angle with radial span. This pitch distribution was selected because it provides the greatest propeller efficiency (η) at our cruise condition (which was convenient because otherwise group Zeta would have had to design its own propeller in order to vary this parameter). Figure 11.8 illustrates the variation in propeller efficiency with advance ratio (J). At the cruise condition, where J is approximately 0.5, this analysis predicts an η value upwards of 0.833 (as shown). During turning, in order to maintain steady level flight, the Valkyrie may increase its flight velocity to stabilize the lift available from the banked geometry. Such a maneuver, which may be necessary to avoid stalling the wing, effectively increases the propeller efficiency, hence improving the propeller's overall performance.

Figures 11.9 and 11.10 illustrate the behavior of the both thrust coefficient and the power coefficient with changes in advance ratio. Each figure demonstrates the expected trends. For a cruise advance ratio of approximately 0.5, Figure 9 yields a thrust coefficient of approximately 0.65, while Figure 7 predicts of power coefficient of 0.044. Each of these values is more than sufficient to meet the propulsive requirements of the Valkyrie. Overall performance, particularly current draw, power available, and rate of climb, are discussed in the following section on performance.

Having discussed all critical design domains, the proceeding discussion evaluates these design selections in the following performance analysis.

Figure 11.8 Propeller Effeciency

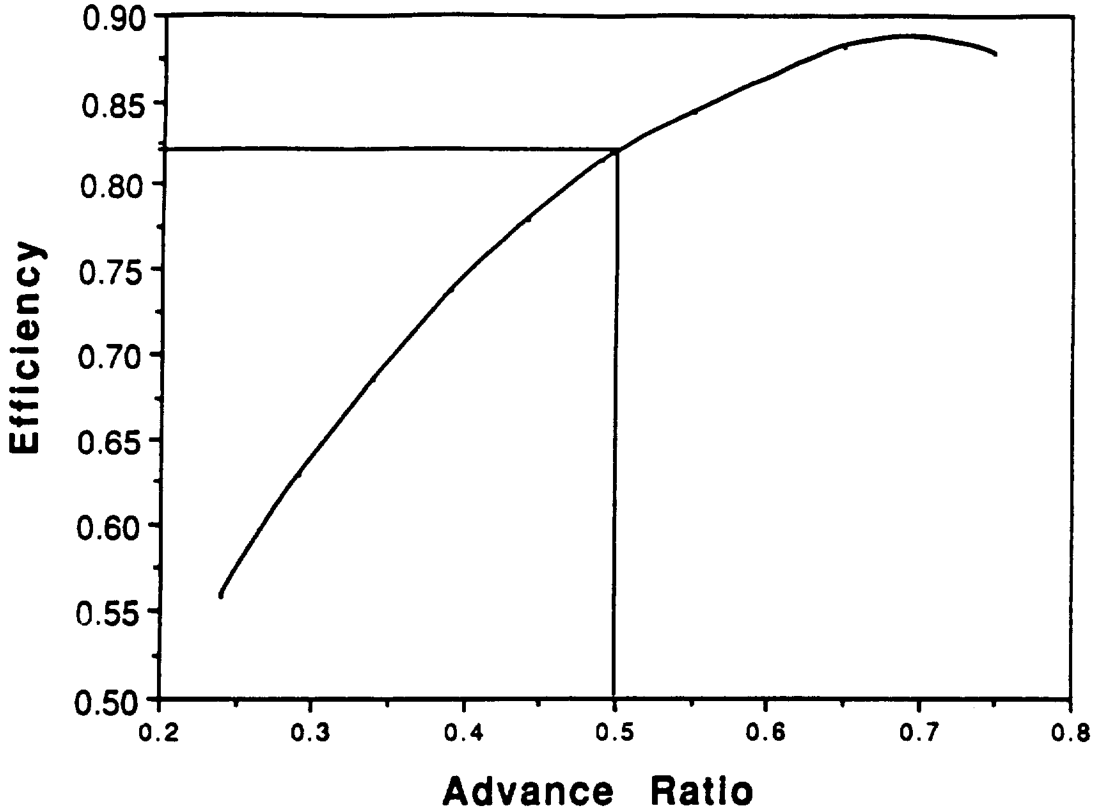


Figure 11.9 Thrust Coefficient vs Advance Ratio

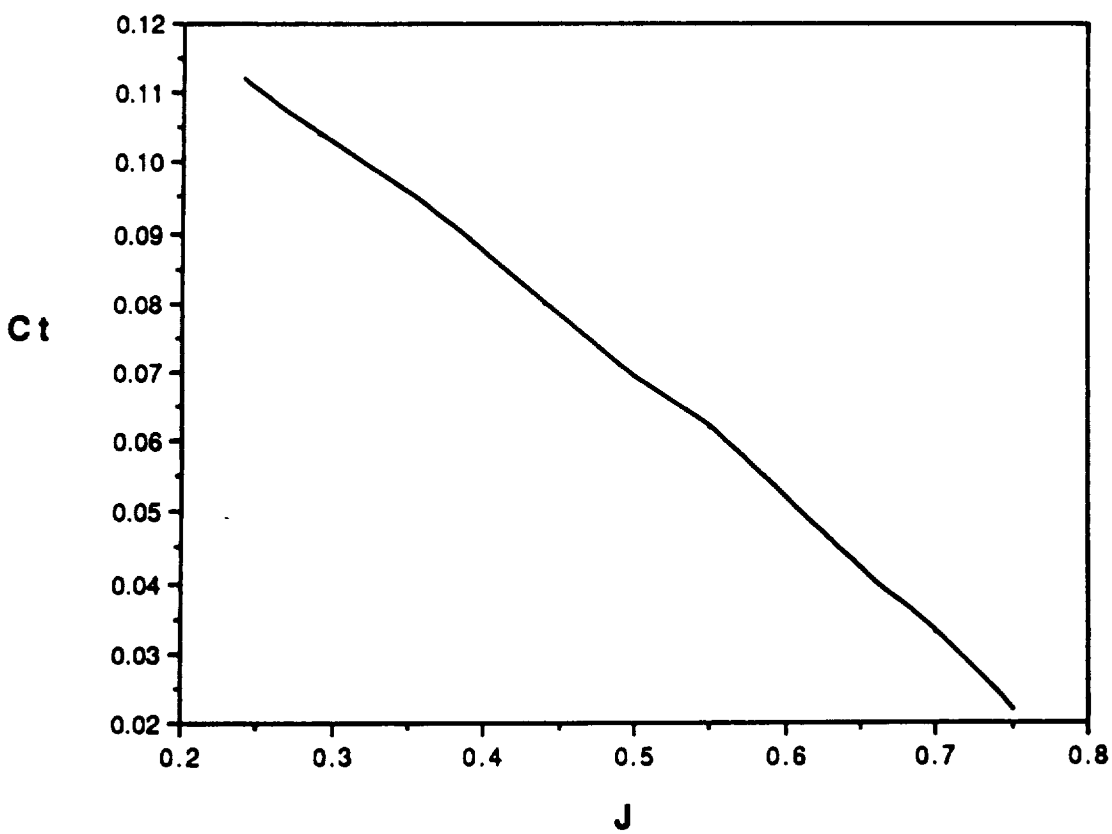
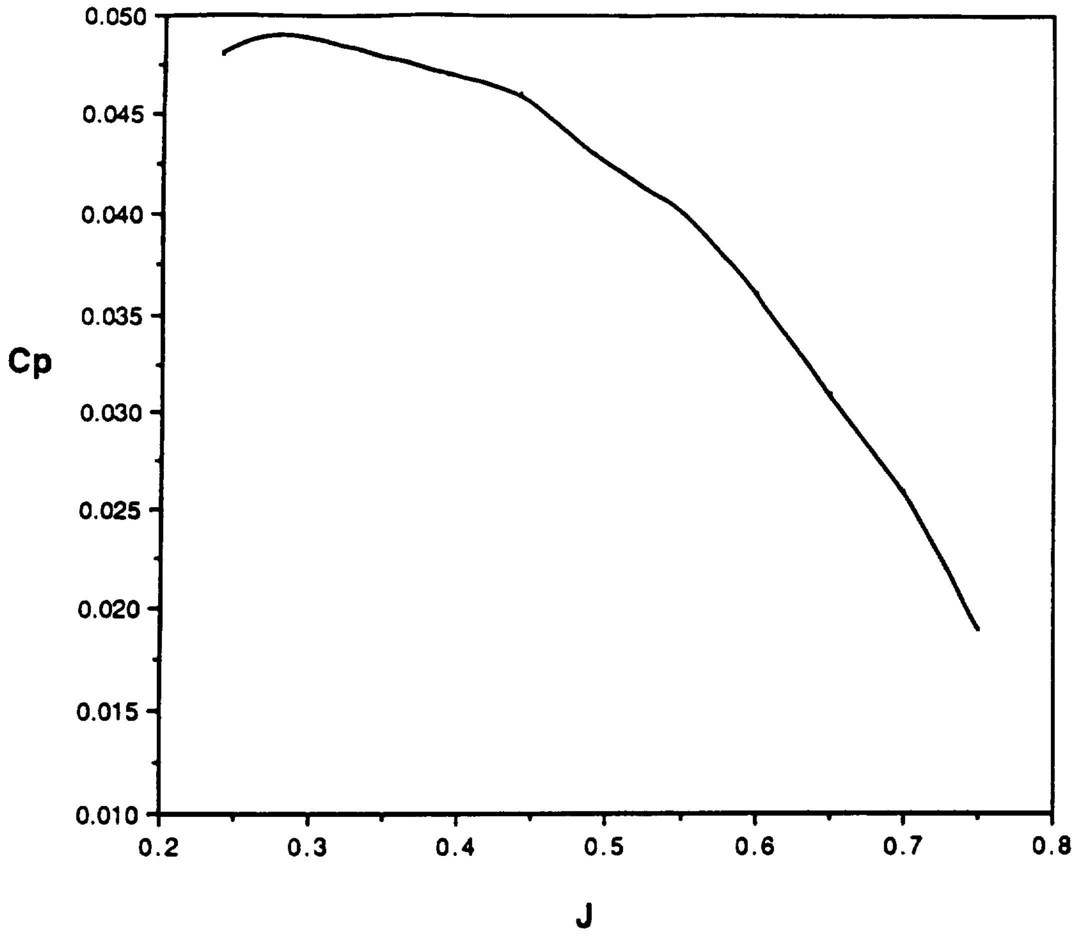


Figure 11.10 Power Coefficient vs Advance Ratio



The following analytical tools were employed in various ways throughout the preceding analysis.

- TK! solver program "Electric Prop"
- Fortran program "Takeoff Perf"
- Fortran program "Power Req/Avail"
- The Apple IIe's Propeller Element Analysis

Performance

Section 12. Elements of Performance for the Valkyrie

The performance analysis of the *Valkyrie* is broken into four main categories: (1) the Take-off / Landing performance; (2) the Lift to Drag relationships needed for steady level flight; (3) the Turning and Rate of Climb performance; and, (4) the *Valkyrie's* Endurance and Range.

12.1 Take-off / Landing

The take-off and landing criteria were set for a maximum runway length of 75 ft. With this requirement in mind, the *Valkyrie* is designed to taxi and takeoff at approximately an eight degree angle of attack set by a front wheel height of 8 inches. The rolling coefficient of friction (during taxi) was estimated to be 0.04 for short grass. The maximum lift coefficient during take-off is 0.824 which generates a take-off velocity 26.1 ft/sec. Using these values, the final take-off distance is estimated between 16 and 25 ft. The use of rotation by the pilot can reduce the ground roll distance by increasing the available lift. However, this rotation may not exceed four degrees for two reasons: (1) The trailing edge of the aircraft would be in too close to the runway, and (2) the stall angle of attack for the aircraft is twelve degrees (as mentioned prior, the aircraft is mounted at an eight degree angle of attack). It should be noted that rotation is not necessary as the wing is already mounted at the take off angle of attack.

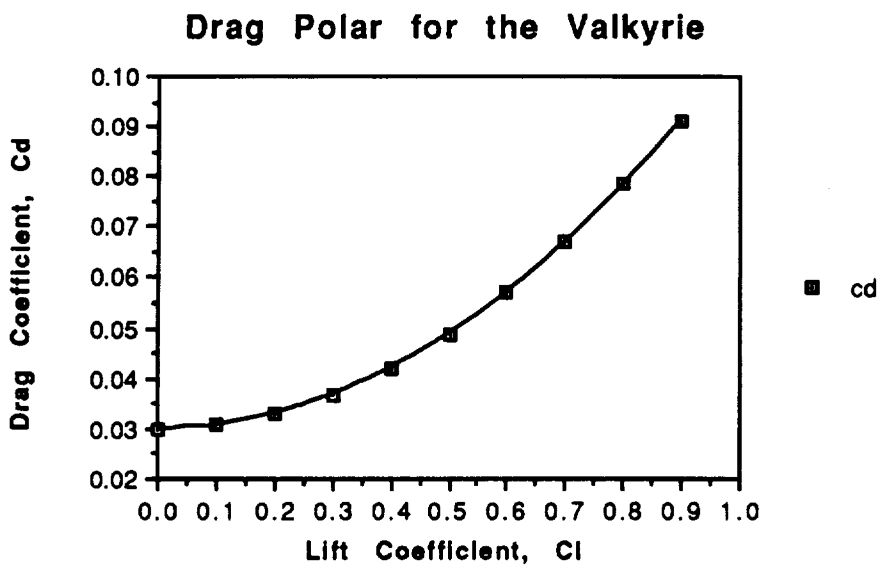
For landing, the optimum glide path angle is -5.46 degrees (equal to the inverse of the maximum lift to drag ratio). The approach and touchdown speed should ideally be the stall speed for the aircraft, 21.67 ft/sec. However, in order to maintain trim conditions, the touchdown speed needs to be 26 ft/sec (the take-off velocity). Following touchdown the aircraft must shut down the motor in order to finally stop at a distance of 58 ft (using the propeller to generate drag). Furthermore, the landing distance will be reduced by applying the elevators and ailerons

differentially (similar to a spoiler technique) in order to create more drag on the *Valkyrie*.

12.2 Lift / Drag relationships

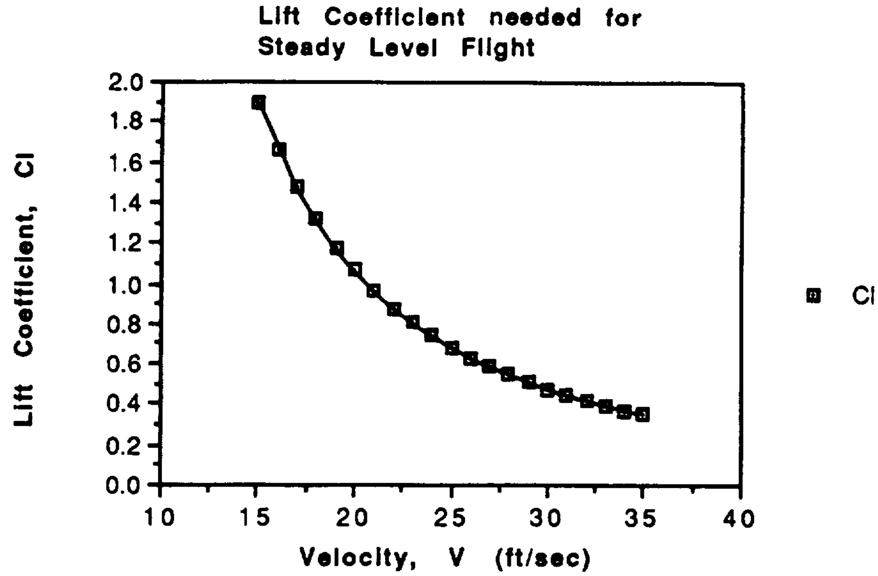
The drag polar equation, $Cd=0.03 + 0.0755\ Cl^2$, for the *Valkyrie* is plotted below, Figure 12.1. From the drag polar, the maximum Lift to Drag ratio, E_m, is 10.5.

Figure 12.1



The lift coefficient needed for steady level flight was tabulated and plotted in the figure below, Figure 12.2. As should be noted in order for the *Valkyrie* to fly at cruise (V_{cruise}=32 ft/sec), the needed trim lift coefficient must be 0.416. The power required to fly at this configuration is 11.85 ft-lb/sec. The drag coefficient for this cruise configuration is 0.043 producing a Lift to Drag ratio, E, of 9.67.

Figure 12.2



12.3 Turning Flight / Rate of Climb

The *Valkyrie* needed to satisfy the requirement that the turning radius could not exceed 60 ft. At the cruise configuration various turning radii were used to determine the subsequent lift coefficient, roll rate, bank angle, and load factor during a turn. These values are listed below in Table 12.1.

Table 12.1 Turning Performance

Turning Radius,R (ft)	Cl	Roll Rate, ω (deg/s)	Bank Angle, ø (deg)	Load factor, n
20.000	.782	91.2	57.535	1.878
25.000	0.674	72.960	51.560	1.618
30.000	0.607	60.800	46.429	1.457
35.000	0.563	52.114	42.040	1.351
40.000	0.532	45.600	38.287	1.278
45.000	0.510	40.533	35.067	1.225
50.000	0.493	36.480	32.290	1.185

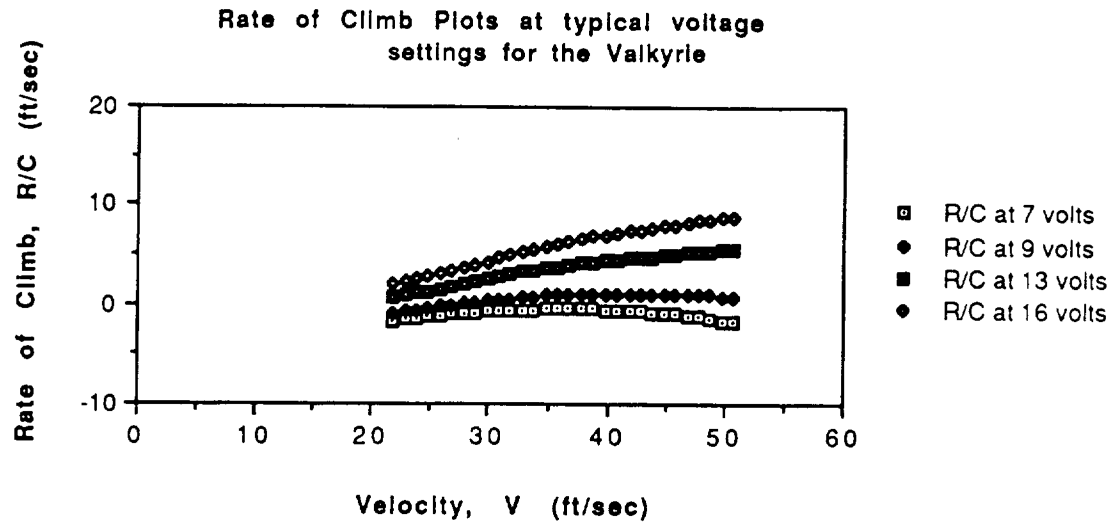
Thus, at cruise with a lift coefficient of approximately 0.42, the *Valkyrie* performs a turn within a 50 ft radius. The reason for choosing the larger turning radius in the

table is because the bank angle for the turn should not exceed 45 degrees. However, if the aircraft is either accelerated or the angle of attack increased during the turn, the *Valkyrie* is capable of turning at a smaller radius.

It should be noted that these values all meet the necessary constraints, the load factor during turn does not exceed the *Valkyrie's* maximum load factor of 2.5. Furthermore, the induced turning lift coefficient does not exceed the maximum lift coefficient (representing stall) of 0.9, for the *Valkyrie*.

The Rate of Climb for the *Valkyrie* is plotted below in Figure 12.3 for various throttle settings (represented by the voltage supplied the batteries) for a range of velocities from 20 to 50 ft/sec. Figure 12.3 indicates that the *Valkyrie's* throttle should be set between 13 and 16 volts in order to produce the most effective rates of climb. The *Valkyrie* is capable of climbing at rates of 2.86 to 5.8 ft/sec over the velocity interval of 28 to 33 ft/sec.

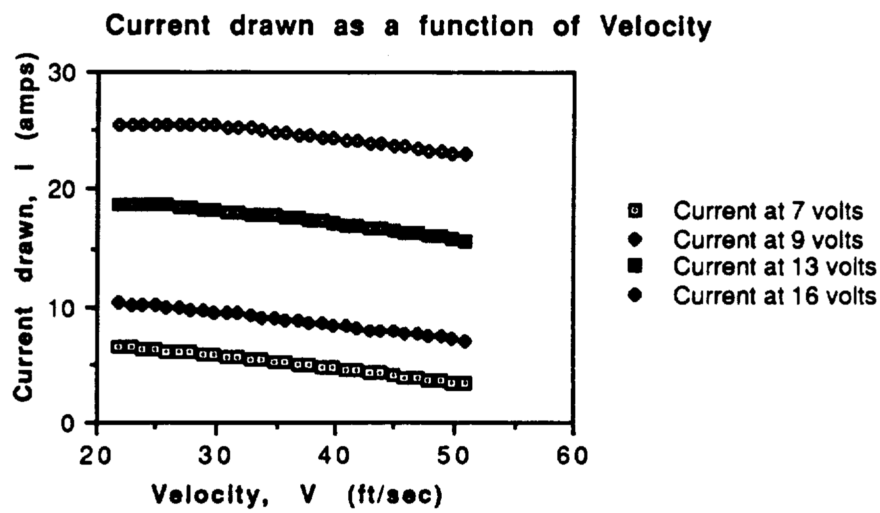
Figure 12.3



12.4 Endurance / Range

The endurance and range depend strongly on the current and voltage drawn by the motor. The following graph, Figure 12.4, depicts the current drawn for four typical voltages as a function of velocity. At cruise velocity and full passenger capacity, the voltage and current were set equal to 6.304 V and 4.25 amps, respectively, to yield a flight time of 423 seconds and an range of 13,545 ft. These values were chosen in order to yield approximately zero rate of climb.

Figure 12.4



The range and flight time vary according to the weight of the aircraft. Thus, the range-payload and endurance-payload diagrams for the *Valkyrie* are shown below in Figures 12.5 and 12.6, for no payload, half payload, and full payload (payload in this case refers to passengers). As the plots display, the endurance and range will increase by 25 seconds and 700 ft. respectively, when there is no payload aboard.

Figure 12.5

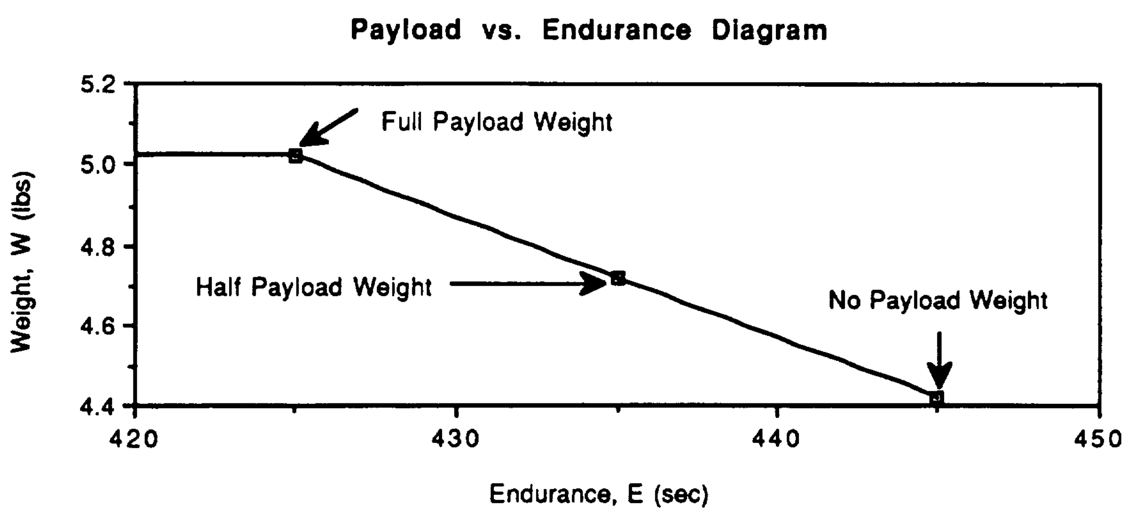
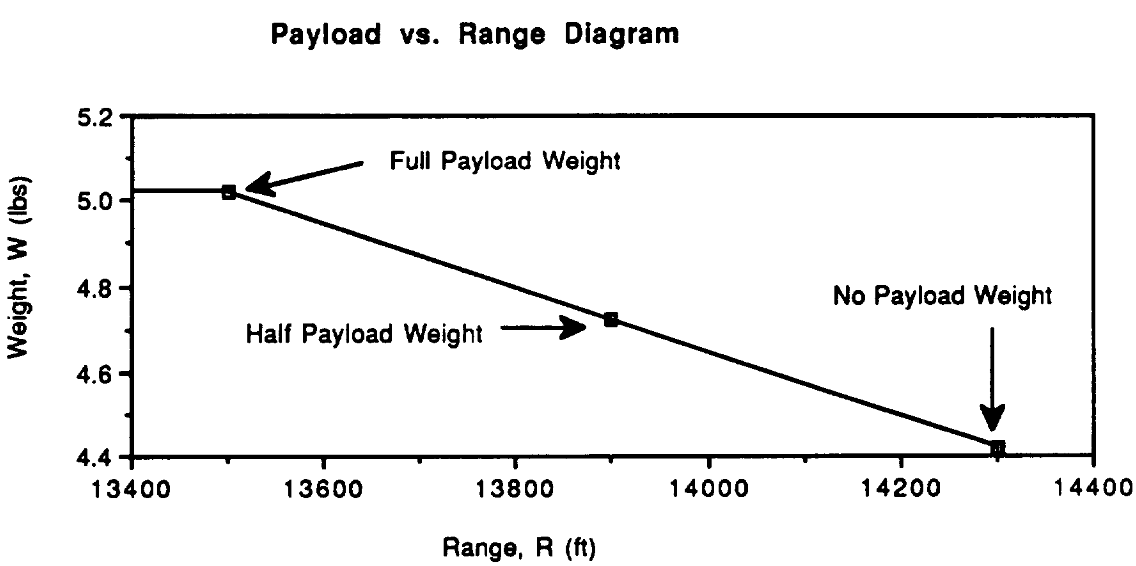


Figure 12.6



Technology Demonstrator

13. *Technology Demonstrator*

13.1 Aerodynamics

Newly acquired construction experience suggests that, because the trailing edge control surfaces were most effectively manufactured as symmetric airfoils, a symmetric airfoil might have been more efficiently employed during construction without any significant loss in performance. Manufacturing chord–varying, reflexed control surfaces proved exceedingly challenging, while unfortunately not providing significant advantages. That is, attempting to precisely measure and cut geometrically complex reflexed edges was more difficult than anticipated.

Obtaining a smooth, even finish on the Mono–Kote also proved tedious and difficult. As a result, areas of wrinkled plastic mar the outer covering of the *Valkyrie*. Though the estimation of the parasite drag coefficient included a 10% increase for this expected skin roughness, the effect of these imperfections on the overall lift of the aircraft remains unknown.

Finally, thin, spanwise, leading edge spars were attached along the ribs near the leading edge of the aircraft in order to support the tight, plastic covering and maintain a true airfoil shape. Unfortunately, these same spars produce undesireable ridges in the covering which may trip the boundary layer into the turbulent region very near the leading edge of the airfoil. Tripping the boundary layer prior to its natural transition point will create more drag due to skin friction than originally expected. At this point, the addition of the leading edge spars to maintain accurate airfoil shape remains problematic, and uncertainty exists as to the advantage of these spars.

13.2 Weights and Balances

The weights of the individual parts developed approximately as expected.

	Weight (lbs)	CG. position (in from lead edge)
Engine w/prop	0.95	1.5
Front wheel	0.19	5.5
Real wheel	2 @ .045	23.
Avionics	0.291	----
Batteries	1.08	2.5
Speed Controller	0.11	7.0
Structure	2.31	14.0
Ballast	1.0	0.33

The specific weight distribution, however, of the integrated components was not entirely anticipated.

13.3 Internal Structure

Installation of the internal structural components proceeded as planned with one exception. Vertical, 1/16 inch, balsa wood plates were installed perpendicular to the ribs in order to increase the structural integrity and thereby reduce the internal stresses.

Another change was implemented to reduce the structural weight and improve the aerodynamic effectiveness of the plastic coating. The proposed half ribs were replaced by sixteenth inch plastic rods strung spanwise. Besides having effectively maintained the shape of the leading edge, this structural alteration also reduced the overall weight of the aircraft.

13.4 Landing Gear Installation

The nose gear is located forward of the center of gravity and is actuated by the rudder servo. Two smaller wheels are located at lower tips of the lateral vertical

stabilizers. The struts are locked into a brass bushing which enables some variability in its length. Since this aircraft does not rotate upon takeoff, such flexibility allows for appropiate changes the fixed takeoff angle of attack so satisfy any unanticipated lift-off requirements.

13.5 Stability and Control

In general, the installation and construction of the various control surfaces and actuation elements proceeded as expected. Elevators and Ailerons are both capable of deflecting to the desire angles (±30°), while the control actuators supply more than sufficient power to perform these manipulations. Some unanticipated circumstances required one alteration in the control capabilities of the center stabilizer and attached rudder. In order to provide both increased control power at this rudder location (increasing the moment arm length) and an expanded clearance for the servo motors, the center rudder was shifted back approximately two inches.

The preponderant stability and control difficulty encountered during construction emerged from the attempt to appropriately position the center of gravity, a topic discussed in detail in the proceeding section.

13.6 Difficulty in C.G. Placement

Properly positioning the center of gravity, a design criteria critical to the pitch stability and control of the aircraft, proved to be quite a challenging task. The center of gravity was conservatively anticipated to lie at 67.6% percent of the mean chord. Unexpectedly, after having manufactured the technology demonstrator, the cg. for structure was located at 82.4% of the mean chord. As construction progressed it quickly became apparent that rear vertical tails and horizontal control surfaces contributed immensely to the overall position of the cg, an effect not entirely anticipated during the design process. This unforeseen circumstance borders on catastrophic for any flying wing design. Subsequently, in an attempt to resolve this

difficultly, the avionics and fuel cells were re-positioned as far forward as height and width constraints would allow in a effort to shift the center of gravity further forward. This adjustment proved insufficient, so with precious time dwindling, a one pound ballast was reluctantly integrated into the nose configuration.

13.7 Propulsive System Installation

Beside the alterations discussed above, mounting the enormous Astro 25 required some spontaneous structural modifications necessary to ensure the integrity of the Balsa wood surrounding this massive thrust producer. The ribs on either side of the engine, as well as the rear mounting board, were re-enforced in two ways. First, spanwise, 1/16 inch, balsa wood support boards were structural integrated into the adjacent between-rib cavities. In addition, 1/8 inch support pylons were inserted at an angle between the adjacent ribs and the rear of the engine in order to supply sufficient restraint to prevent the engine from taking off without the rest of the plane. Finally, hinged access panels were installed above the engine so to provide access to the engine and associated components.

Section 14. Concluding Remarks

Given the findings of Group ζ, the *Valkyrie* flying wing concept is the best design option for the specified mission. By concentrating on the large volume passenger routes of the northern, central continent, the *Valkyrie* has been designed to carry a minimum of 100 passengers. The flying wing design results in the most efficient aircraft design as it minimizes the drag penalties conventional aircraft experience. The one component aircraft lead to ease of production and maintenance. Of all of the factors, the most impressive aspect of the *Valkyrie* is it's large passenger to weight ratio. When compared to a conventionally configured aircraft operating the same routes, the *Valkyrie* proves it's efficiency and profitability.

Future derivative aircraft include the expansion of the central section of the *Valkyrie* to accomodate an even larger passenger volume. As a result of its sturdy, yet light, construction, the *Valkyrie* will be the dominant leader in terms of Aeroworld customer/operator and passenger satisfaction.

Appendices

References:

1. Dunn, Patrick F., "Electric Motor Propulsion", Notre Dame, IN

2. Lab Design Handout

3. "LinAir for the Macintosh", Version 1.4, Desktop Aeronautics, Stanford, CA, 1987-90.

4. Nelson, Robert C., Flight Stability and Automatic Control, McGraw-Hill Book Company, New York, 1989.

5. Swift, Richard, "Swiftos for the Macintosh", Notre Dame, IN

```
REM   LinAir Helper v1.0
REM   created by David A. Bustamante
REM   Group Zeta

CLEAR
DIM   SemiArea(3),Semispan(3),Taper(3),Sweep(3),Dihedral(3)
DIM   Xroot(3),Yroot(3),Zroot(3),RootInc(3),TipInc(3)
DIM   CD0(3),CD1(3),CD2(3),panels(3),y(3)

DEF FNchord(yspan)=-.285714285714#*yspan+23/12

   REM   Rough estimate of center of gravity location
      w.str=1.125
      w.motor=.69
      w.batteries=1.4
      w.payload=.6
      w.misc=1.265
      structure=.25*Cr*w.str
      motor=2/12*w.motor
      batteries=9/12*w.batteries
      payload=.4*Cr*w.payload
      misc=.4*Cr*w.misc
      total=w.str+w.motor+w.batteries+w.payload+w.misc
      cg=(structure+motor+batteries+payload+misc)/total
   REM   Center of gravity position specified at 30% root chord.  Above
        section provides rough estimate of cg travel.
      cg=0.575

OPEN "clip:" FOR OUTPUT AS #1
REM   Planform Reference
      Ct=11/12
      Cr=23/12
      Area =(Ct+Cr)/2*7
      Span=7
      Xref =cg
      Yref =0
      Zref =0
      elements=3
      INPUT "Angle of attack: ";Alpha
      Mach = .02

REM   Define element #1

      INPUT "% chord of flap: ";percent.flap
      Semispan(1)=3.5
      SemiArea(1)=(1-percent.flap)*(Ct+Cr)/2*Semispan(1)
      Taper(1)=Ct/Cr
      LESweep=ATN(((1-percent.flap)*(Cr-Ct))*2/Span)
         y(1)=(1-percent.flap)*Cr-Ct*.75*(1-percent.flap)-.25*Cr*(1-percent.flap)
```

```
REM    Sweep is the angle of the quarter chord across the span
   Sweep(1)=ATN(y(1)*2/Span)
   INPUT "Dihedral: ";Dihedral(1)
   Xroot(1)=.25*Cr*(1-percent.flap)
   Yroot(1)=0
   Zroot(1)=0
   RootInc(1)=0
   TipInc(1)=0
   CD0(1)=.0095826
   CD1(1)=-5.4477E-04
   CD2(1)=1.7273E-04

   INPUT "Number of Panels for Element #1: ";panels(1)

REM    Define element #2

   INPUT "Semi-Span of elevator: ";Semispan(2)

SemiArea(2)=(percent.flap*Cr+percent.flap*FNchord(Semispan(2)))/2*Semispan(2)
   Taper(2)=(percent.flap*FNchord(Semispan(2)))/(percent.flap*Cr)
     y(2)=.25*percent.flap*Cr-.25*percent.flap*FNchord(Semispan(2))
 REM    Sweep is the angle of the quarter chord points across the span
   Sweep(2)=-ATN(y(2)/Semispan(2))
   Dihedral(2)=Dihedral(1)
   Xroot(2)=(1-percent.flap)*Cr+.25*percent.flap*Cr
   Yroot(2)=0
   Zroot(2)=0
   RootInc(2)=0
   TipInc(2)=0
   CD0(2)=.0095826
   CD1(2)=-5.4477E-04
   CD2(2)=1.7273E-04
   INPUT "Number of Panels for Elevator: ";panels(2)

REM    Define element #3:  The ailerons

   Semispan(3)=(Span/2)-Semispan(2)
   SemiArea(3)=(percent.flap*Ct+percent.flap*FNchord(Semispan(2)))/2*
          Semispan(3)
   Taper(3)=(percent.flap*Ct)/(percent.flap*FNchord(Semispan(2)))
     y(3)=.25*percent.flap*FNchord(Semispan(2))-.25*percent.flap*Ct
 REM    Sweep is the angle of the quarter chord points across the span
   Sweep(3)=-ATN(y(3)/Semispan(3))
   Dihedral(3)=Dihedral(2)
   Xroot(3)=(1-percent.flap)*Cr+.25*percent.flap*Cr-y(2)
   Yroot(3)=Semispan(2)
   Zroot(3)=0
   RootInc(3)=0
   TipInc(3)=0
```

```
      CD0(3)=.0095826
      CD1(3)=-5.4477E-04
      CD2(3)=1.7273E-04
      INPUT "Number of Panels for Aileron: ";panels(3)

FOR loop2 = 1 TO 3
    Sweep(loop2) = Sweep(loop2)*57.29578
NEXT loop2

REM    Create LinAir File
a$="!"
   PRINT #1,a$,"Input data file for LinAir"
   PRINT #1,a$,"Reference values:"
   PRINT #1,a$,"Area","Span","Xref ","Yref","Zref","Mach","Alpha","#elements"
   WRITE #1,Area,Span,Xref,Yref,Zref,Mach,Alpha,elements
   PRINT #1, a$;"Element Properties:"
FOR loop = 1 TO 3
   PRINT #1,a$,"Semi-Area","Semi-Span","Taper ","Sweep","Dihedral"
   WRITE #1,
SemiArea(loop),Semispan(loop),Taper(loop),Sweep(loop),Dihedral(loop)
   PRINT #1,a$,"Xroot","Yroot","Zroot ","Root Inc.","Tip Inc."
   WRITE #1, Xroot(loop),Yroot(loop),Zroot(loop),RootInc(loop),TipInc(loop)
   PRINT #1,a$,"CD0","CD1","CD2 ","# of panels"
   WRITE #1, CD0(loop),CD1(loop),CD2(loop),panels(loop)
NEXT loop
   PRINT   #1,"end"
CLOSE #1
END
```

```
C   AERO 441
C   AEROSPACE DESIGN
C    INDIVIDUAL TRADE STUDY
C
C   MICHAEL J. BURKE
C   GROUP ZETA
C   DUE THURSDAY 21, MARCH 1991
C
C   PROGRAM TO CALCULATE THE PAYLOAD CAPACITY OF THE VALKYRIE
C
C               PROGRAM VARIABLE DICTIONARY
C
C          CR    =     ROOT CHORD
C          CT    =     TIP CHORD
C           B    =     WING SEMI-SPAN
C           HS    =      SPAN WISE SPACING OF PASSENGERS
C                     INCLUDES "BREATHING ROOM" AND SPACE
C                     REQUIRED FOR RIB STRUCTURAL ELEMENTS
C          CS    =     CHORD WISE SPACING OF PASSENGERS
C                     INCLUDES "BREATHING ROOM" AND SPACE
C                     REQUIRED FOR SPAR STRUCTURAL ELEMENTS
C           VS    =      VERTICAL "HEADROOM" OF PASSENGERS
C                     VS+1.5 EQUALS MINIMUM THICKNESS
C                    REQUIRED FOR PASSENGER PLACEMENT
C          Y(I,J) =     THICKNESS AT SPAN LOCATION I AND
C                   CHORD LOCATION J
C          S     =     WING PLANFORM AREA
C          AR    =     WING ASPECT RATIO
C          N(I)  =     # OF PASSENGERS THAT CAN BE PLACED IN
C                    A CHORD WISE FASHION AT SPAN LOCATION I
C           NTOT  =      TOTAL NUMBER OF PASSENGERS CARRIED IN
C                   HALF OF WING
C          X100  =      MAXIMUM DISTANCE FROM CENTER OF WING
C                   REQUIRED TO ACCOMMODATE 100 PASSENGERS
C          NA(I) =     NUMBER OF AISLES
C
C
   DIMENSION Y(30,18), N(30), BX(30), FX(30), NA(30)
    OPEN (UNIT=1, FILE='2R212.DAT')
    OPEN (UNIT=2, FILE='TRADE.TXT')
C
C   INPUT NECESSARY DATA
C
   HS=1.8125
   CS=1.6
   VS=1.7
   B=42.
 1  WRITE (*,*) 'PLEASE ENTER ROOT CHORD (in)'
   READ (*,*) CR
```

```
      WRITE (*,*) 'PLEASE INPUT WING PLANFORM AREA (ft^2)'
      READ (*,*) S
      S=S*144.
      NTOT=0
C
C     ASSEMBLE CHORD EQUATION
C     LOAD SHAPE MATRIXES
C
      CT=(S-CR*(B+1.))/(B-1)
      X100=1000.
      AR=(2*B)**2/S
      CSLOPE=(CT-CR)/(B-1)
      DO 20 I=1,30
        REWIND (1)
        CHORD=CR+CSLOPE*(HS/2.+HS*REAL(I-1))
        WRITE (*,*) CHORD
       DO 10 J=1,18
         READ (1,*) XX, YU, YL
         Y(I,J)=CHORD*(YU-YL)
 10      CONTINUE
 20    CONTINUE
C
C     CHECK FOR LENGTHS WHERE "PASSENGERS" WILL FIT
C
      DO 40 I=1,30
        IF (HS/2.+HS*REAL(I-1)+1. .GT. B) GOTO 40
        LF=19
        LB=0
        CHORD=CR+CSLOPE*(HS/2.+HS*REAL(I-1))
        REWIND (1)
       DO 30 J=1,18
         READ (1,*) XX,YU,YL
         IF (Y(I,J) .GE. VS) THEN
          IF (J .LT. LF) THEN
           XF=XX
           LF=J
           FX(I)=XF*CHORD-CS/2
          ENDIF
          IF (J .GT. LB) THEN
           XB=XX
           LB=J
           BX(I)=XB*CHORD+CS/2
          ENDIF
         ENDIF
 30      CONTINUE
        BL=(XB-XF)*CHORD
        NA(I)=1
        N(I)=INT(BL/CS)
        NN=NTOT+N(I)
```

```
      IF (NTOT .LT. 50. .AND. NN .GE. 50.) X100=HS/2.+HS*REAL(I-1)+1.
      IF (N(I) .GT. 0) NTOT=NN
 40   CONTINUE
C
C     OUTPUT RESULTS
C
      WRITE (2,*)
      WRITE (2,*)
      WRITE (2,*)
      WRITE (2,*) 'ROOT CHORD      ', CR
      WRITE (2,*) 'TIP CHORD       ', CT
      WRITE (2,*) 'WING SPAN       ', B*2
      WRITE (2,*) 'WING AREA       ', S/144
      WRITE (2,*) 'ASPECT RATIO    ', AR
      WRITE (2,*) 'SPAN FOR 100    ', X100
      WRITE (2,*) '# PASSENGERS    ', NTOT*2
      WRITE (2,*)
      WRITE (2,*)
      WRITE (2,*)
      DO 50 I=1,30
      IF (HS/2.+HS*REAL(I-1)+1. .GT. B) GOTO 50
      SL=HS/2.+HS*REAL(I-1)+1.
      IF (N(I) .LE. 0) GOTO 50
      WRITE (2,*) SL, FX(I), BX(I), N(I), NA(I)
 50   CONTINUE
      WRITE (*,*) 'DO YOU WISH TO TRY ANOTHER SET OF PARAMETERS'
      WRITE (*,*) 'PLEASE ENTER 1 FOR YES 2 FOR NO'
      READ (*,*) IT
      IF (IT .EQ. 1) GOTO 1
      STOP
      END
```